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Physical activity assessment with accelerometers

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OBJECTIVE: Evaluation of motion sensors, specifically accelerometers, as an objective tool for the assessment of physical activity in large populations, over periods long enough to be representative of normal daily life and with minimal discomfort to the subjects.
METHOD: Review of validation studies of accelerometers with indirect calorimetry as a reference method. Accelerometers were commercially available one-axial accelerometers: Caltrac®, Computer Science Application (CSA) accelerometer, Mini Motionlogger Actigraph; the tri-axial accelerometer Tritrac-R3 D; and an tri-axial accelerometer for movement registration (Tracmor) from our laboratory.
RESULTS: There is no clear difference for correspondence between indirect calorimetry and accelerometer counts during level walking, whether one-axial or tri-axial and placed at the wrist, hip or low back. Sedentary activities are better reflected with a tri-axial accelerometer than with a one-axial accelerometer. Two accelerometers were validated in free living conditions with doubly labeled water. The highest correlation between accelerometer output and activity induced energy expenditure was found for Tracmor.
CONCLUSIONS: From all accelerometers tested, the tri-axial accelerometer for movement registration is an objective method that can be used to distinguish differences in activity levels between individuals and assess the effect of interventions on physical activity within individuals.

Keywords: activity induced energy expenditure; indirect calorimetry; body movement

Introduction

Physical activity is generally considered to be a central factor in the etiology, prevention and treatment of obesity. To get more insight into the interaction between daily physical activity and obesity, an objective and reliable method for the assessment of physical activity in free-living subjects is required. The method should be suitable to measure physical activity in large populations over relatively long and representative periods, and with minimal discomfort to the subjects. There is already a large number of techniques for the assessment of physical activity, which can be grouped into five general categories: behavioural observation, questionnaires (including diaries, recall questionnaires and interviews), physiological markers (like heart rate), calorimetry and motion sensors.

Validated techniques of estimating habitual physical activity are needed to study the relationship between physical activity and obesity. The greatest obstacle to validating field methods of assessing physical activity in humans has been the lack of an adequate criterion to which techniques may be compared. The intercorrelation of various field methods may be of some value, but because there are errors in all methods it is impossible to determine the true validity of any one of them in doing so.[1] However, calorimetry (and more specifically the doubly labeled water method) is becoming a gold standard for the validation of field methods for assessing physical activity. Methods thus evaluated below include motion sensors, which meet the criteria of being objective and suitable to measure physical activity in large populations over periods long enough to be representative of normal daily life and with minimal discomfort to the subjects. Motion sensors for the assessment of physical activity have evolved from mechanical devices like pedometers to electronic accelerometers. Here we will deal with accelerometers, with the potential to reflect not only the occurrence of body movement (like a pedometer), but also the intensity of movement. Currently there are several accelerometers available for the assessment of physical activity. Commercially available examples are the Caltrac® (Hemokinetics, Madison, WI), the Computer Science Application (CSA) accelerometer (Computer Science and Applications Inc., Shalimar, FL), the Mini Motionlogger Actigraph (Ambulatory Monitoring Inc., Ardsley, NY), and the Tritrac-R3 D accelerometer (Hemokinetics, Madison, WI). Additionally, there are accelerometers developed

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for non-commercial purposes like the tri-axial accelerometer for movement registration (Tracmor) from our laboratory.[2,3]

Methods

The Caltrac is a one-axial accelerometer for vertical movement, 9.7×7.0×1.3 cm, 78 g. Energy expenditure is estimated by entering the subject's age, height, weight and gender. Activity counts are displayed when predetermined constants are entered in place of the subject's personal data. A cumulative energy expenditure or movement count is displayed on a small liquid crystal screen. The Actigraph is a one-axial accelerometer, 6.3×8.9×1.9 cm, 85 g. The monitor interfaces with a computer for programming and downloading the data. The CSA is a one-axial accelerometer, 6.6×4.3×1.5 cm, 70 g. Movement counts are stored and subsequently downloaded *via* a personal computer (PC). The Tritrac-R3 D is a tri-axial accelerometer, 11.1×6.7×3.2 cm, 170 g. Energy expenditure is estimated by entering the subject's age, height, weight and gender. Data can be downloaded and used for the calculation of body acceleration, by subtracting the calculated resting energy expenditure, based on published predictive equations, from the registered energy expenditure.[4] The accelerometers developed in our laboratory consisted initially of a tri-axial sensor, weighing about 25 g, connected to a data acquisition unit, 4×6×8 cm, 350 g (Tracmor 0) or 11×7×3.5 cm, 250 g (Tracmor 1).[5,6] Activity counts over one minute intervals are stored for up to three weeks and can be downloaded. Recently, sensor and data acquisition were combined in one system, 7×2×0.8 cm, 30 g (Tracmor 2, Philips Research, Eindhoven, The Netherlands).

Physical activity is defined as body movement, produced by skeletal muscles and resulting in energy expenditure.[7] Accelerometers for the assessment of physical activity, are based on the measurement of body movement, that is, the dynamic component of physical activity.

Accelerometers cannot be used to measure the static component in exercises, like weight lifting or carrying loads. However, in normal daily life, it is assumed that the effect of static exercise on the total level of physical activity is negligible.

Validation of accelerometers is performed against energy expenditure. Energy expenditure can be measured by direct or indirect calorimetry. Indirect calorimetry, measuring gas exchange associated with the oxidation of energy substrates, is the commonly adopted method for the validation of accelerometers. Indirect calorimetry measures total energy expenditure (TEE), resulting in heat production and external work. Validation studies include measurements during defined activities, measurements in a controlled environment, and measurements in free living conditions. The method for indirect calorimetry involves, respectively, breathing through a mouthpiece, mask or hood into a gasanalyser, a respiration chamber, and doubly labeled water. The time resolution is, respectively, minutes, half hours and several days. In all circumstances, the end result is a measure for total energy expenditure.

TEE can be divided in three components, resting or basal metabolic rate (RMR, BMR), diet induced energy expenditure (DEE) and activity induced energy expenditure (AEE). The components vary with, respectively, time of day, food intake pattern and activity pattern. In short term validation studies, that is, studies over minutes or hours, (instead of days), food intake and time of day should be standardized to leave the activity pattern as the only variable.

Comparing activity levels between individuals needs correction of energy expenditure for body size. Published studies used several options, generally dividing TEE or AEE by weight or weight to an exponent between 0.5 and 1.0. The rationale of the latter is that physical activity is a mix of weight-dependent and non-weight dependent activities. Unfortunately, there is no generalizable coefficient for adjusting TEE or AEE.[8] A frequently used method to quantify physical activity is by expressing TEE as a multiple of RMR or BMR. It assumes that the variation in TEE is due to body size and physical activity. Adjusting TEE for RMR or BMR implies the use of metabolic body mass as the denominator or body mass to the exponent 0.66 to 0.75.

Results

All accelerometers mentioned, Caltrac, CSA, Actigraph, Tritrac and Tracmor, have been validated during short-term protocols with defined activities. Caltrac, Tritrac and Tracmor were validated in the controlled environment of a respiration chamber. Caltrac and Tracmor were validated with doubly labeled water in free living conditions.

Table 1 summarizes validation studies during short-term protocols with defined activities. Placement of the accelerometer was at the low back or hip or on the wrist. Activities were level walking and in some studies sedentary tasks as well. Correspondence, expressed as the Pearson product-moment correlation between accelerometer counts and AEE, ranged from 0.25−0.91, both observed with the Caltrac. Two studies did not present correspondence in this way. Meijer *et al*[2] presented a standard error of estimate for AEE from accelerometer counts of 79 $J.min^{-1}.kg^{-1}$. Sherman *et al*[14] presented the correlation between measured TEE and calculated TEE from subject characteristics and accelerometer counts. There is no clear difference for correspondence between

Table 1 Calorimetric validation studies of accelerometers during short-term protocols with defined activities

Accelerometer	*Placement*	*Type of activities*	*Subjects (n)*	*Correspondence*	*Reference*
Caltrac	Low back	Level walking	25	$r=0.91$	9
	Hip	Level walking	15	$r=0.82$	10
	Hip or back	Level walking	56	$r=0.25-0.73$	11
Actigraph	Wrist	Physical tasks	15	$r=0.73$	12
	Wrist	Sedentary tasks	15	$r=0.46$	12
CSA	Wrist	Level walking	28	$r=0.89$	13
Tracmor 0	Low back	Sedentary/physical tasks	16	–	2
Tracmor 1	Low back	Sedentary/physical tasks	13	$r=0.89$	3
Tritrac	Low back	Level walking	16	–	14

CSA = Computer Science Application.

calorimetry and accelerometer counts during level walking, whether one-axial or tri-axial and placed on the wrist, hip or low back. Sedentary activities might be better reflected with an tri-axial accelerometer (Tracmor 1) than with a one-axial accelerometer (Actigraph), although the placement of the accelerometers was also different for the two different instruments.

Three accelerometers were validated in a respiration chamber, Caltrac, Tracmor 1 and Tritrac. Bray *et al*[15] observed 40 girls, age range from 10–16 y, over 24 h intervals, participating in normal sedentary activities and two 20 min cycle ergometer exercise sessions. A Caltrac accelerometer was placed on each hip, one programmed to estimate energy expenditure and the other to assess activity counts. Daily energy expenditure, excluding the cycle ergometer sessions (to reflect energy expenditure for sedentary activity), was compared with Caltrac counts and Caltrac estimated energy expenditure. Data were available in 29 subjects. Caltrac estimated energy expenditure was, and Caltrac counts only was not correlated with chamber assessed energy expenditure, $r=0.81-0.87$ ($P<0.001$) and $r=0.11-0.14$ (not statistically significant (ns)), respectively. Bouten *et al*[16] observed 13 young men over 36 h intervals, two nights and the intervening day. Seven subjects performed a protocol with activities of moderate intensity, including walking and bench stepping, and the other six performed the same activities at a lower intensity. Tracmor 1 was worn during the non-sleeping interval of the 36 h observation on a waistbelt at the low back. A correlation of 0.72 was found between TEE over 24 h and accelerometer output. AEE, calculated over 30 min intervals, correlated with accelerometer output ($r=0.89$) as observed during defined activities (Table 1).[3] Chen and Sun[4] observed 125 adults, 53 men and 72 women, over two 24 h intervals, separated by at least one day, one 24 h interval with 'normal' activities and the other one with a defined exercise protocol. The subjects wore a Tritrac on the right hip. Data were presented as calorimeter measured energy expenditure and Tritrac estimated energy expenditure, the latter based on RMR predicted from gender, age, height and weight, and on AEE predicted from body acceleration. A correlation of 0.91 was found between calorimeter measured energy expenditure and Tritrac estimated energy expenditure, using the Tritrac model. No data on the relationship between measured energy expenditure and body acceleration were presented.

Two accelerometer types were validated in free living conditions with doubly labeled water. Johnson *et al*[17] observed 31 children with the Caltrac over three days of a 13–16 d measurement interval of TEE. Caltrac counts did not significantly explain variation in TEE after adjusting for gender, fat free mass and fat mass of the subjects. Bouten *et al*[6] observed 30 adult subjects, 14 women and 16 men, over seven days, while Tracmor 1 was worn 13.6 ± 1.4 h/d. The highest correlation was found for the relationship between Tracmor output and TEE/RMR ($r=0.58$, $P<0.001$). The correlation was improved to 0.73 after correction for Tracmor values arising from vibrations produced by transport means.

Discussion

Evaluation of accelerometers for the assessment of physical activity is complicated despite the choice of energy expenditure as a uniform validation standard. Caltrac and Tritrac routinely display TEE calculated from the programmed subject characteristics gender, age, height and weight, and measured body acceleration. Validation studies thus primarily evaluate the conversion of subject characteristics into an energy estimate. A clear example is the study of Bray *et al,*[15] where Caltrac estimated energy expenditure was, and Caltrac counts only was not correlated with chamber assessed energy expenditure. The Caltrac can be programmed to monitor uncorrected movement counts. Published studies do not mention this option for the Tritrac, the only commercial tri-axial accelerometer so far.

The majority of the short-term protocols used level walking as the one and only defined activity, that is, five out of eight (Table 1). For one-axial accelerometers, level walking generated body acceleration was closer related to AEE than body acceleration during sedentary activities as might be expected.[12] AEE during sedentary activities correlates better with the sum of body acceleration in all three directions than with the vertical displacement of the body, as monitored by one-axial accelerometers.[3] For tri-axial accelerometers, AEE during sedentary activities, as well as AEE during walking, could be estimated with the same accuracy.[3]

Accelerometer output is influenced by the place of attachment to the human body. Body sites are differentially active, depending on the behaviour engaged in and movements of one site are not necessarily correlated with movements of other sites. Theoretically, the highest accuracy for the prediction of AEE will be reached by using multiple accelerometers. The disadvantage is the discomfort to the subject and potentially interference with the physical activity to be measured. Using AEE as a reference for physical activity, AEE is a function of the body acceleration and the mass of the body displaced. One accelerometer, attached close to the center of mass of the body, seems to be the optimal choice. In fact the majority of studies with body fixed accelerometers for activity assessment, use the hip, waist or low back as the site of attachment.

Accelerometers are instruments for the assessment of dynamic activities. Physical activity, defined as body movement produced by skeletal muscles and resulting in energy expenditure, includes static and dynamic activity.[7] Static activity involves static exercise and maintaining body position. The impact of static exercise like weight lifting on the total level of normal daily physical activity is generally assumed to be negligible for the average subject. The impact of postures like sitting or standing on AEE has to be recognized. The energy expenditure of maintaining body position per unit of time, is negligible, compared to the energy expenditure of dynamic activities, however, the time spent on sitting and standing can add up to several hours per day. For a 70 kg subject, AEE for sitting, is around 0.72 kJ.min^{-1}, AEE for standing is around 0.96 kJ.min^{-1}, and a figure for the daily average AEE of moderately active subjects is 3.60 kJ.min^{-1}.[3,6,18] On the other hand, one rarely sits or stands without any body movement, as shown by comparing the accelerometer output for sitting and standing with the daily average, respectively, 800 ± 600 and 1100 ± 800, and 1133 ± 260 counts.min^{-1}.[6] Static activities thus become dynamic activities.

Theoretically there is no instrument capable of assessing physical activity by monitoring acceleration at one body site only (see above). All devices are a compromise between validity and subject comfort. Validity and subject comfort have to be evaluated in free living conditions. The indicated method for validity evaluation in free living conditions is the measurement of RMR in combination with doubly labeled water measured TEE. Surprisingly, of the four available studies in literature so far, the earliest two are only published in abstract form.[6,17,19,20] Gretebeck *et al*[19] and Heyman *et al*[20] measured TEE with doubly labeled water, while subjects were wearing a Caltrac programmed to display TEE. Caltrac TEE was significantly related to doubly labeled water TEE, but the mean TEE result was lower than doubly labeled water TEE, in both studies. However, as mentioned before, Caltrac TEE is primarily a result of the conversion from subject characteristics into an energy estimate. The third study, using the Caltrac in the 'activity counts' mode, concluded that it was not a meaningful predictor of AEE.[17] Bouten *et al*[6] published a doubly labeled water evaluation of an tri-axial accelerometer for movement registration (Tracmor 1). Similar research is needed for the Tritrac.[14]

Subject comfort in wearing an accelerometer is determined by site of attachment, size and weight of the accelerometer. The majority of studies with body fixed accelerometers for activity assessment use the hip, waist or low back as the site of attachment. We prefer direct attachment on the skin of the low back with an elastic belt around the waist.[6] Attachment on the skin with an elastic belt gives direct contact with the body and allows for invisible coverage of the accelerometer with clothing. Arranging the accelerometers from small to big or from light to heavy results in Tracmor 2 (11 cm^3, 30 g), CSA (43 cm^3, 70 g). Caltrac (88 cm^3, 78 g), Actigraph (107 cm^3, 85 g), Tritrac (238 cm^3, 170 g), Tracmor 1 (270 cm^3, 275 g) and Tracmor 0 (192 cm^3, 375 g). CSA is the smallest commercial available accelerometer. Devices the size of a Tritrac, Tracmor 1 and Tracmor 0 are larger than subjects can accommodate without hindrance. Meijer *et al*[21] mentioned that subjects complained when wearing Tracmor 0 for a whole week. To enhance wearing comfort, Tracmor 2 was developed and might be produced as a commercial product in the near future. It combines features like tri-axial, minute by minute data storage for up to three weeks, computer downloading of the data and minimal size.

Applications of Tracmor 0, Tracmor 1 and Tracmor 2 have been in exercise training studies and in the assessment of physical activity in underweight and overweight subjects.[21–26] Meijer *et al*[21] measured with Tracmor 0 the effect on the physical activity level of a five-month training program for endurance running, while simultaneously measuring TEE and AEE. The subjects were 16 women and 16 men, aged 36 ± 11 y with a body mass index (BMI) 24.9 ± 2.1 kg.m^{-2}. Training induced an increase in accelerometer output and in AEE. Tracmor output showed no effect of exercise on physical activity during the rest of the day. Van Etten *et al*[24] investigated with Tracmor 1 the effect on the physical activity level of an 18-week weight-training program, while simultaneously measuring ADMR and AEE. The subjects were 18 men, aged 33 ± 6 y with a BMI of 23.8 ± 2.5 kg.m^{-2}. Again, training induced an increase in AEE and Tracmor output showed no effect of exercise on non-training physical activity. However Meijer *et al,*[26] examining with Tracmor 2 the effect of a 12-week training program of moderate intensity in elderly subjects, observed an increase in physical activity on training days, which was compensated with a decrease in physical activity on non-training days. Thus, the effect of exercise training on non-training physical activity seems to be age dependent.

Meijer *et al*[22] compared with Tracmor 0 and with the doubly labeled water method the physical activity level of 11 lean and 11 obese women and men over a seven-day period. The activity level in the obese was comparable to that in the lean. More detailed studies with Tracmor 1 showed no significant differences in accelerometer counts between subjects with normal weight, anorexia nervosa and morbid obesity.[25] However, in the anorectics, accelerometer output was significantly related to BMI. Subjects with a BMI $\geq 17\,kg.m^{-2}$ were equally or more active than the control subjects, while subjects with a BMI $< 17\,kg.m^{-2}$ were equally or less active than the control subjects.[23] In the morbid obese subjects, five of the eight had a low activity level and the other three had a high activity level.

Conclusion

The tri-axial accelerometer is an objective method that can be used to distinguish differences in activity levels between individuals and to assess the effect of interventions on physical activity within individuals.

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