Daily physical activity assessment: comparison between movement registration and doubly labeled water.

special communication

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CARLIJN V. C. BOUTEN, WILHELMINE P. H. G. VERBOEKET-VAN DE VENNE, KLAAS R. WESTERTERP, MAARTEN VERDUIN, AND JAN D. JANSSEN
Department of Human Biology, University of Limburg, 6200 MD Maastricht; and Faculty of Mechanical Engineering, Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands

Bouten, Carlijn V. C., Wilhelmine P. H. G. Verboeket-Van De Venne, Klaas R. Westerterp, Maarten Verduin, and Jan D. Janssen. Daily physical activity assessment: comparison between movement registration and doubly labeled water. *J. Appl. Physiol.* 81(2): 1019–1026, 1996.—The use of movement registration for daily physical activity assessment was evaluated during a 7-day period in 30 free-living subjects. Body movement was registered with a Tracmor motion sensor consisting of a triaxial accelerometer and a data unit for on-line processing of accelerometer output over 1-min intervals. Average Tracmor output was correlated against four different energy estimates: *1*) average daily metabolic rate (ADMR), determined with doubly labeled water; *2*) ADMR − sleeping metabolic rate (SMR; determined in a respiration chamber); *3*) (ADMR − SMR) per kilogram of body mass; and *4*) the overall physical activity level (PAL = ADMR/SMR). The highest correlation was found for the relationship between Tracmor output and PAL (r = 0.58). After correction for Tracmor values arising from vibrations produced by transportation means, this correlation was improved to 0.73. There was no difference between Tracmor output and PAL in discriminating between overall activity levels with "low" (PAL $<$ 1.60), "moderate" (1.60 $\leq$ PAL $\leq$ 1.85), and "high" (PAL $>$ 1.85) intensity. It is concluded that the Tracmor can be used in free-living subjects to distinguish among interindividual as well as intraindividual levels of daily physical activity.

daily activity; accelerometry; energy expenditure; free-living conditions

THE ASSESSMENT OF DAILY PHYSICAL ACTIVITY requires an objective method that can be used under normal daily living conditions over prolonged periods of time with minimal discomfort to subjects. Currently, the doubly labeled water method is generally accepted as the "gold standard" for physical activity assessment in free-living subjects. This method determines the average daily metabolic rate (ADMR) and, together with an estimate of resting energy expenditure, provides a reliable measure of energy expenditure associated with physical activity over periods of 1–3 wk (17, 19, 24). Usually ADMR is expressed as a multiple of the resting energy expenditure to indicate the overall daily physical activity level (PAL), which is now favored by the World Health Organization (29). Alternately, the difference between ADMR and resting energy expenditure, eventually corrected for the diet-induced thermogenesis, is used as the absolute equivalent of physical activity. The doubly labeled water method, however, can only be used to indicate the average level of daily physical activity and does not provide information about activity patterns in time. Furthermore, the high cost of the stable isotopes (currently at least $500 for an adult subject) and the need for sophisticated analysis techniques limit its applicability to small populations. Nevertheless, the method is ideally suited as a reference technique for the evaluation of other methods for physical activity assessment.

Movement registration with body-fixed accelerometers seems to offer promising possibilities to reflect daily physical activity patterns in population studies. In 1981, Wong et al. (28) were the first to develop a portable accelerometer for the assessment of physical activity in relation to energy expenditure. The device could be attached to the waist and registered accelerations parallel to the longitudinal axis of the trunk. The integrated absolute value of accelerometer output was significantly related to oxygen consumption in a group of subjects performing standardized activities under laboratory conditions [r = 0.74 (12)]. The development of this uniaxial accelerometer eventually resulted in the design of the commercially available Caltrac, which has been frequently evaluated concerning its validity and applicability during the last decade. Most evaluations, however, are performed in the laboratory and do not provide information about the validity and usefulness in free-living subjects, whereas the few evaluations under daily living conditions are performed against rather poor criterion measures over limited periods of time (8, 18).

Regarding the multidirectional characteristics of human movement, it is often suggested that the use of triaxial accelerometers may be superior to that of uniaxial accelerometers like the Caltrac in predicting daily physical activity (2, 9, 15). Recently, Bouten et al. (4) developed a triaxial accelerometer based on three separate uniaxial accelerometers. Comparisons with indirect calorimetry showed strong significant relationships between accelerometer output and energy expenditure for physical activity during sedentary and walk-

ing activities [r = 0.95 (4)] as well as during a 1-day period of standardized activity in a respiration chamber [r = 0.89 (3)]. The present study was directed at evaluating this triaxial accelerometer for the assessment of daily physical activity in free-living subjects. A portable data unit was used for the on-line recording and storage of accelerometer output over 1-min intervals. The triaxial accelerometer and data unit together are referred to as the Tracmor. During a 1-wk period, physical activity recorded with the Tracmor was compared with four different energy measurements: *1*) ADMR, determined with doubly labeled water; *2*) ADMR − sleeping metabolic rate (SMR; determined in a respiration chamber); *3*) (ADMR − SMR) per kilogram of body mass; and *4*) the ratio between ADMR and SMR (ADMR/SMR = PAL). Diet-induced thermogenesis was assumed to be a constant fraction of ADMR, thus adding little to the variation in these energy measures.

The field experiment was preceded by two short-term calibration experiments in the laboratory to examine whether individual relationships between Tracmor output and energy expenditure established during these experiments can be used to estimate the energy expenditure from Tracmor output in daily life. Furthermore, the influence of transportation in daily life, scored by the subjects in activity logs, was studied because vibrations produced by transportation means may influence accelerometer output and hence the relationship with energy expenditure (7, 16).

METHODS

Subjects. The subjects were 17 men and 15 women who were recruited from a 6-mo follow-up study on the effect of diet composition on energy expenditure (25). One man and one woman were excluded because of missing data. Mean age, height, body mass, and body mass index of the remaining 30 subjects are presented in Table 1. All subjects were certified to be in good physical health by a staff physician and gave informed consent to participate in the study after the procedures were explained to them. The subjects had full-time or part-time employment, with professions varying from office administrator to surgical nurse to dog trimmer. Most subjects were engaged in leisure-time sports activities. The experimental protocol was approved by the Ethics Committee of the University of Limburg.

Protocol. The experimental protocol consisted of a 2-wk period during which the subjects were followed in their natural free-living environment, preceded by a 36-h stay in a respiration chamber (2 nights and the intervening day) and a 15-min walking experiment. The respiration chamber and walking experiments were performed to determine the individual relationships between Tracmor output and energy expenditure for physical activity during standardized activity (walking) and free, uncontrolled activity (respiration chamber). These experiments were used as calibration measurements for the field study. SMR was determined during both nights in the respiration chamber over a 3-h interval between 0230 and 0700 with the lowest level of activity, as indicated by a movement-detection system in the chamber based on Doppler radar. The two SMR values were averaged, and the average SMR was used in all further calculations. After the calibration experiments, the subjects wore the Tracmor during the waking hours of a 7-day period in their normal daily life situation. In addition, they kept an activity log. ADMR in daily life was measured by doubly labeled water over a 2-wk period. At the start and end of this period, the subjects' body mass was measured to investigate energy balance. A schematic representation of the protocol is shown in Fig. 1.

Table 1. *Subject characteristics*

	Men (n = 16)	Women (n = 14)	Total (n = 30)
Age, yr	28.4 ± 4.9	25.6 ± 4.7	27.1 ± 5.01
Height, m	1.80 ± 0.04*	1.65 ± 0.05	1.73 ± 0.09
Body mass, kg	79.9 ± 8.4*	63.5 ± 6.3	72.2 ± 11.1
Body mass index, kg/m^2	24.6 ± 2.4	23.4 ± 2.0	24.1 ± 2.3

Values are means ± SD; n, no. of subjects. *Significant difference between men and women, $P < 0.001$.

Movement registration. A triaxial accelerometer (50 × 30 × 8 mm, 16 g), consisting of three uniaxial piezoresistive accelerometers (ICSensors type 3031-010) was used to register body movement. With an elastic belt around the waist, the accelerometer was attached to the lower back of the subjects, with measurement directions along the anteroposterior, mediolateral, and longitudinal axes of the trunk. A flexible cable ran from the accelerometer to a portable data unit for on-line acquisition, processing, and storage of acceleration signals. This unit measures 110 × 70 × 35 mm and weighs 250 g, including batteries. In the data unit, acceleration signals from the three measurement directions were amplified and high-pass (0.11-Hz) and low-pass (20-Hz) filtered to attenuate the DC response of accelerometer output and frequencies outside the frequency range of voluntary human movement. Acceleration signals are then further processed with a miniaturized data logger (Tattletale 5F, Onset Computer) that is programmed and started from a computer via a serial interface. In the present study, the data logger was programmed to calculate the sum of the rectified and integrated acceleration curves from all three measurement directions, as described by Bouten et al. (4). The time period for integration was set at 1 min, and the output obtained from the accelerometer and data unit was expressed as counts per minute. In this paper, this output is referred to as the Tracmor output. The Tracmor output is stored in a 512-kB 16-bit data-memory chip and can be directed to a computer for subsequent analysis. The memory is reset by disconnecting the supply voltage to the accelerometer and data unit, which is provided by batteries. Two 9-V 1,200-mA·h batteries are required to register and process acceleration signals over a period of 8 days. Batteries, data logger, and other electronic components are kept in a housing of polyvinyl chloride. This housing can be opened by the investigator for replacement of batteries and calibration of the accelerometer. Calibration is performed by omitting the high-pass filters in the data unit. The DC response can then be used to determine the sensitivity of the uniaxial accelerometers by altering their orientation with respect to the field of gravity. Normally, the sensitivity of each measurement direction is set at 1,000 counts/min, corresponding to an acceleration of 1 g (1 g = 9.812 m/s^2 at the experimental site). The data unit is worn around the waist in a small bag (fanny pack), or it is attached directly to a waist belt by using slits on both sides of the polyvinyl chloride housing. In the present study, 10 identically calibrated Tracmors were used, which all performed consistently throughout the total experimental period. No changes in sensitivity of the accelerometers were found during calibrations before and after the measurements. However, data from two subjects were excluded due to an insufficient power supply from exhausted batteries.

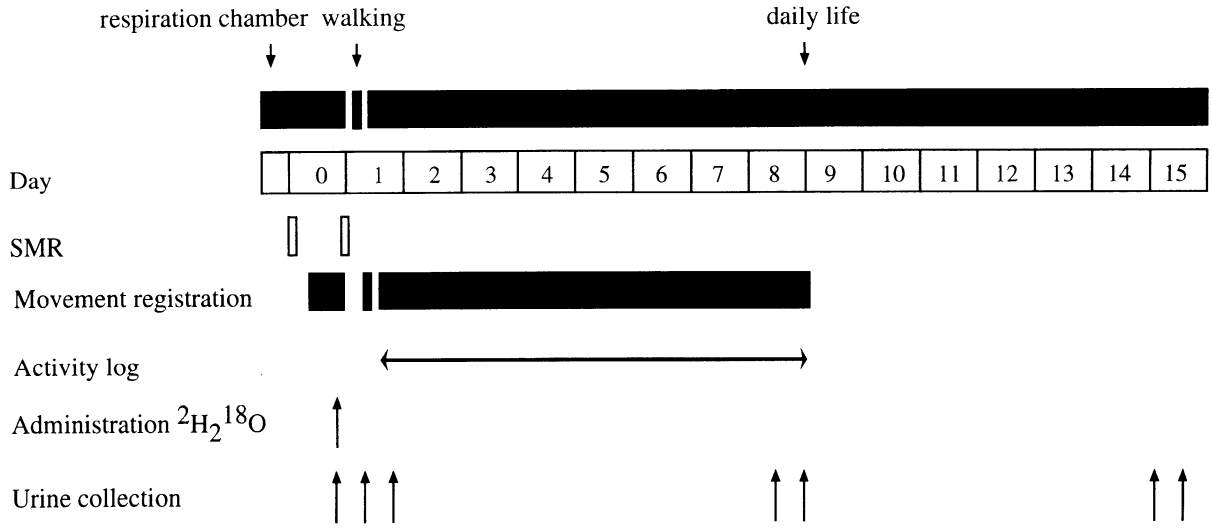

Fig. 1. Schematic representation of experimental protocol. SMR, sleeping metabolic rate.

Calibration measurements. The subjects arrived at the laboratory on the evening before *day 0* to stay in the respiration chamber (21). During the waking hours (0800–2230), the Tracmor output was determined while the subjects were allowed to move freely. Meals and snacks were provided by the investigator. Energy intake for maintenance of energy balance was estimated to be 1.4 times the basal metabolic rate estimated from age, height, sex, and body mass according to Harris and Benedict (6). The determination of O_2 consumption and CO_2 production in the respiration chamber is described elsewhere (22). Instantaneous total energy expenditure (EE_{tot}; in W) was calculated every 5 min from O_2 consumption rates and CO_2 production rates according to Weir (23). Next, energy expenditure for physical activity (EE_{act}) was calculated as (EE_{tot} − SMR) if it is assumed that diet-induced thermogenesis shows little variation between subjects (27). EE_{act} was then averaged over 30-min intervals and related to 30-min averages of Tracmor output in each subject to determine individual regression equations between these variables. In addition, the ratio between the whole day averages of EE_{act} and Tracmor output was used as a single calibration factor to indicate the average EE_{act} per count. The same procedure was followed for Tracmor output vs. EE_{tot} as a multiple of SMR.

After leaving the respiration chamber on the morning of *day 1*, the subjects walked on a motor-driven treadmill (Quinton) at 3, 4, and 5 km/h while synchronous measurements of body movement and total energy expenditure (Mijnhardt, Oxyconbeta) were made. Each velocity stage lasted for 5 min. The energy estimates EE_{act} and EE_{tot}/SMR were calculated over the last 2 min of each velocity stage and correlated against the average Tracmor output during these intervals. Again individual regression equations and EE_{act} or EE_{tot}/SMR per count were determined.

Field study. The subjects were instructed to wear the Tracmor from *day 1* to *day 8* during waking hours, except during bathing, taking a shower, or swimming. In addition, they kept an activity log to record the time periods when they were wearing the equipment. This information was used to calculate the average weekly Tracmor output using only the time intervals when the equipment was worn. In the activity log, sleeping hours and time engaged in one of eight activity categories were also recorded. Activity categories comprised *1*) lying down, *2*) sitting, *3*) standing, *4*) walking, *5*) cycling, *6*) domestic work, *7*) sports and exercise, and *8*) transportation by motorbike, car, train, bus, or metro. These categories covered most daily activities and could be scored in a standardized way without the need for the subjects to go into details. The subjects were asked to complete the activity log four times a day and to recall the activities of the last hours. The time resolution of the log was 15 min.

ADMR was measured over 2 wk with doubly labeled water according to Westerterp et al. (26). Briefly, the subjects drank a weighed amount of ^{18}O and ^2H in the evening of *day 0* (2200) after a baseline urine sample was collected (Fig. 1). The dosage of the stable isotopes was based on body mass to create an ^{18}O excess of 300 parts/million and a ^2H excess of 150 parts/million. Further urine samples were collected from the second and last voidings on *days 1, 8*, and *15*. Urine samples were analyzed with an isotope ratio mass spectrometer (Aqua Sira, VG-Isogas), and CO_2 production was calculated from isotope ratios in baseline and *day 1, 8*, and *15* samples with the equations from Schoeller et al. (20). CO_2 production was converted to ADMR by using an energy equivalent based on the individual macronutrient composition of the diet determined from dietary records. Because Tracmor recordings were made during the first week of the field study, only ADMR values of this first week were used for further calculations. The energy compartment (ADMR − SMR) was used as the absolute energetic equivalent of daily physical activity, again if a negligible effect of diet-induced thermogenesis was assumed. This compartment was then expressed per kilogram of body mass to allow comparison among subjects with different body masses. Furthermore, the overall PAL was determined by expressing ADMR as a multiple of SMR. This measurement accounts for the active cell mass that is reflected in the SMR (10). Values for ADMR and (ADMR − SMR) are expressed in watts and for (ADMR − SMR) per kilogram of body mass in watts per kilogram.

Statistics. Data are presented as means ± SD. Paired *t*-tests (two tailed) were used to evaluate differences within subjects, whereas differences between sexes were evaluated with unpaired *t*-tests. Associations among variables were analyzed with simple and multiple linear regression analyses, and regression equations, correlation coefficients (Pearson's *r*), and SEs of estimate (SEEs) were computed. Correspondence among separate regression lines was tested by analysis of covariance, with the *x*-variable as covariate, to test both the slopes and the *y*-intercepts of the lines. The correspondence between the two methods of physical activity assess-

ment in assigning subjects to different activity categories was analyzed with a Wilcoxon signed rank test.

RESULTS

Calibration measurements. For each subject, eight different calibration factors, indicating the association between Tracmor output and energy expenditure, were determined: four during walking and four during uncontrolled activity in the respiration chamber. During walking, all subjects showed a significant relationship between Tracmor output and EE_{act} ($r = 0.92 \pm 0.09$, range 0.63–0.99). Analysis of covariance showed no difference between regression lines for men and women. The regression equation, using the whole group averages for Tracmor output and EE_{act} for each walking velocity, is given by

$$EE_{act} = 69.89 + 4.43 \times 10^{-2} \times \text{Tracmor output (counts/min)} \quad (1)$$

with SEE = 0.07 W, $r = 0.99$, and $P < 0.01$. The ratio between EE_{act} and Tracmor output during walking was, on average, 0.09 ± 0.04 W/count. Because SMR is a constant variable in each subject, correlations between Tracmor output and EE_{tot} as a multiple of SMR were identical to Tracmor output vs. EE_{act}. The regression equation for the whole group was

$$EE_{tot}/SMR = 2.18 + 4.56 \times 10^{-4} \times \text{Tracmor output (counts/min)} \quad (2)$$

with SEE = 0.04, $r = 0.98$, and $P < 0.01$. The average value per Tracmor count was $1.74 \times 10^{-3} \pm 5.07 \times 10^{-4}$. In the respiration chamber, individual correlations between Tracmor output and energy values ranged from 0.46–0.89 (mean $r = 0.70 \pm 0.19$). Here, also, no difference among regression lines for men and women was found. The regression equations, using whole group averages, are given by

$$EE_{act} = 22.08 + 5.29 \times 10^{-2} \times \text{Tracmor output (counts/min)} \quad (3)$$

with SEE = 1.21 W, $r = 0.86$, and $P < 0.001$, and

$$EE_{tot}/SMR = 1.18 + 5.59 \times 10^{-4} \times \text{Tracmor output (counts/min)} \quad (4)$$

with SEE = 0.05 W, $r = 0.89$, and $P < 0.001$. The calibration factors, indicating the average energy values per Tracmor count in the chamber, were 0.07 ± 0.02 W/count for EE_{act} and $1.83 \times 10^{-3} \pm 8.69 \times 10^{-4}$ per count for EE_{tot}/SMR.

Field study. Figure 2 shows the raw Tracmor output in time, averaged over 10-min intervals, for two subjects during one weekday of the field study. Figure 2*A* represents the activity pattern, quantified by Tracmor output, of a female subject engaged in cleaning activities. In the evening, this subject went out to dance. Figure 2*B*, on the other hand, shows the more regular activity pattern of a female subject mainly engaged in sedentary activities.

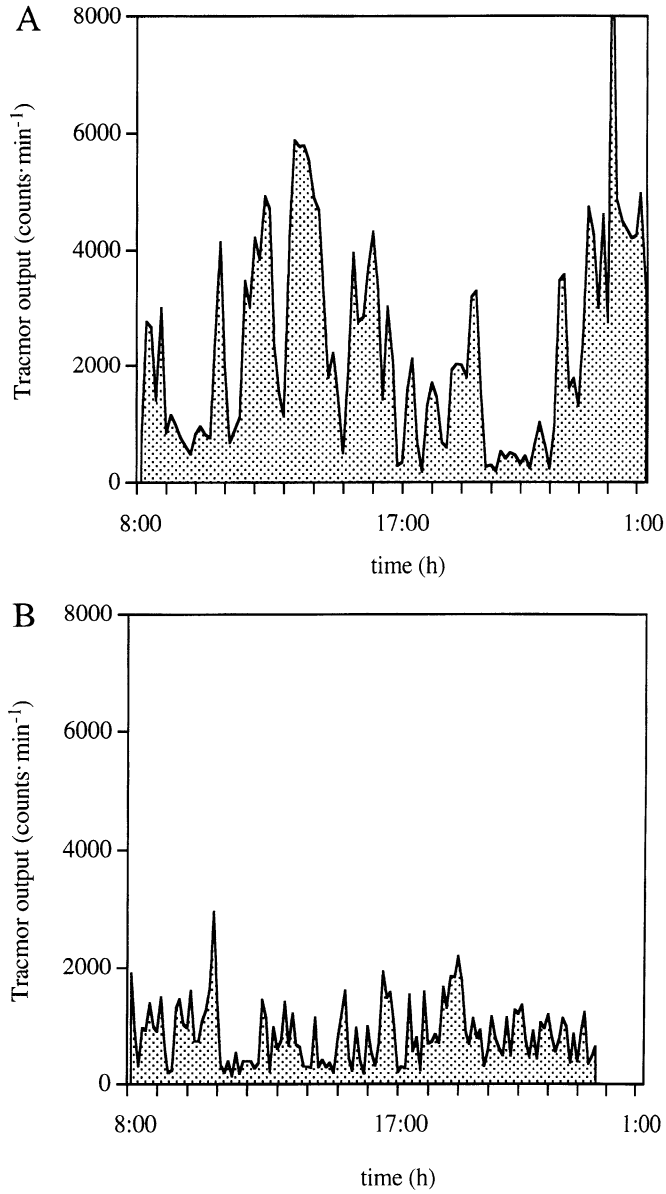

Fig. 2. Tracmor outputs in time during a weekday in a subject mainly engaged in cleaning activities (*A*) and during a weekday in a subject mainly engaged in sedentary work (*B*).

By using the scores in the activity logs, the complete range in instantaneous Tracmor output per activity category was determined for each individual. The ranges, combined with the means ± SD per activity category, for the entire experimental group are given in Fig. 3. During "lying," the range in instantaneous Tracmor output varied from 0 to ~1,650 counts/min, whereas during sports activities, maximal values of 8,000 counts/min were reached. During "transportation," the range in Tracmor output was much larger. In particular, during riding in buses, extremely high values (up to 54,000 counts/min) were found. Such high values were also observed in subjects sitting on the back of a bike or motorbike, a type of transport that was also assigned to the transportation category. Because

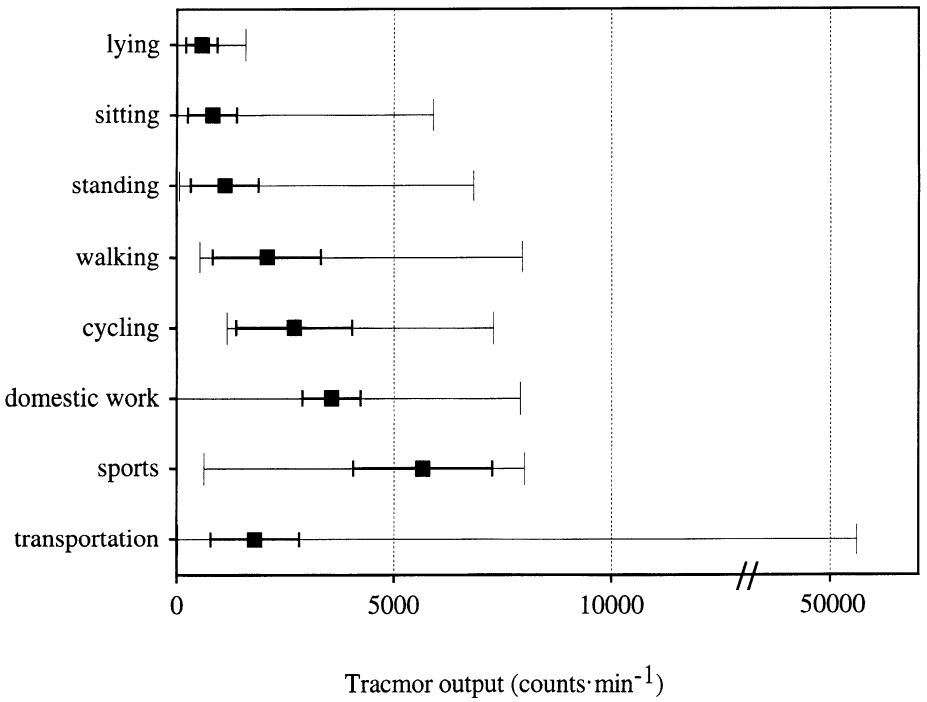

Fig. 3. Mean values (■), SDs (thick solid lines), and ranges (thin solid lines) of Tracmor output per activity category in daily life.

these high values did not correspond to any of the other activity categories, it was assumed that they were not produced by voluntary human movement but resulted from the means of transportation per se. Therefore, all Tracmor data with a value > 8,000 counts/min (the maximum of the other categories) were excluded from the results to correct for this influence. This resulted in a significant difference between the 7-day averages of raw and corrected Tracmor outputs ($P = 0.003$).

Average raw and corrected Tracmor values are shown in Table 2 for men and women, together with the values of all measured energy estimates, the daily periods when subjects were asleep, and the daily duration of Tracmor monitoring in the field study. As determined from body mass measurements, all subjects were in energy balance during the field experiment (mean change 0.00 ± 0.69 kg). A significant difference in SMR was found between men and women, mainly due to differences in physical characteristics between the sexes (Table 1). The difference in ADMR between men and women could also be attributed to differences in physical characteristics because the energy equivalents for physical activity [(ADMR − SMR), (ADMR − SMR)/body mass, and PAL] were similar for both groups. Women spent significantly more hours sleeping than did men.

Table 2. *Average Tracmor output with and without correction for values >8,000 counts/min, ADMR, SMR, (ADMR − SMR), (ADMR − SMR)/body mass, PAL, and daily sleeping and monitoring hours in field study*

	Men ($n = 16$)	Women ($n = 14$)	Total ($n = 30$)
Tracmor output, counts/min	1,069 ± 198	1,206 ± 300	1,133 ± 260
Corrected Tracmor output,§ counts/min	1,004 ± 184	1,152 ± 314	1,073 ± 263
ADMR, W	152.3 ± 20.9†	126.3 ± 20.9	140.2 ± 24.6
SMR, W	89.2 ± 7.1‡	71.1 ± 4.5	80.7 ± 10.9
(ADMR − SMR), W	63.2 ± 19.0	55.3 ± 18.2	59.5 ± 19.0
(ADMR − SMR)/body mass, W/kg	0.8 ± 0.3	0.9 ± 0.3	0.8 ± 0.3
PAL	1.71 ± 0.21	1.78 ± 0.26	1.75 ± 0.24
Sleeping, h	8.0 ± 0.6*	8.6 ± 0.8	8.3 ± 0.7
Monitoring, h	13.8 ± 1.6	13.3 ± 0.9	13.6 ± 1.4

Values are means ± SD; n, no. of subjects. Tracmor, triaxial accelerometer and portable data unit for registration of body movement; ADMR, average daily metabolic rate; SMR, sleeping metabolic rate; PAL, daily physical activity level (ADMR/SMR). Significant difference between men and women: *$P < 0.05$; †$P < 0.01$; ‡$P < 0.001$. §Significant difference between corrected and uncorrected Tracmor output, $P = 0.003$.

Correlations between Tracmor output and the separate energy estimates (Table 3) were higher for corrected than for uncorrected average Tracmor outputs and became stronger when ADMR was reduced by SMR and normalized for body mass. The highest correlation was found for the relationship between PAL and the

Table 3. *Correlation coefficients and standard errors of estimate for average Tracmor output vs. ADMR, (ADMR − SMR), (ADMR − SMR)/body mass, and PAL*

	Tracmor Output		Corrected Tracmor Output	
	r	SEE	r	SEE
ADMR, W	0.17	25.1	0.25	24.7
(ADMR − SMR), W	0.37*	18.3	0.47†	17.4
(ADMR − SMR)/body mass, W/kg	0.53†	0.3	0.63‡	0.2
PAL	0.58‡	0.20	0.73‡	0.15

r, Correlation coefficient; SEE, standard errors of estimate. Correlations are calculated for average Tracmor outputs with and without correction for values > 8,000 counts/min. Significant relationship: *$P < 0.05$; †$P < 0.01$; ‡$P < 0.001$.

corrected average Tracmor output (r = 0.73). The relationship between these variables is shown in Fig. 4 for the pooled data of all subjects. Because the regression lines for PAL vs. corrected average Tracmor output did not differ between men and women, this pooling of data was justified.

The use of individual regression equations, established during the calibration experiments in the respiration chamber and during walking, did not result in any improvement in the prediction of energy expenditure from Tracmor recordings in the field. Application of the individual EE_{act} per Tracmor count based on the respiration chamber calibrations, on the other hand, caused a significant improvement in the prediction of ADMR and (ADMR − SMR). In both cases, the correlation was improved to 0.60. Predictions of (ADMR − SMR)/body mass and PAL were not improved by any of the calibration factors. The use of Tracmor in combination with sleeping hours, however, resulted in a significant improvement in the prediction of PAL. Multiple regression analysis showed an increase in the correlation coefficient from 0.73 to 0.79 (SEE = 0.14; $P < 0.001$) when information on individual sleeping hours was added to the information on body movement. The pooled regression equation is given by

$$\text{PAL} = 0.46 + 5.83 \times 10^{-4} \times \text{Tracmor output (counts/min)} + 0.85 \times \text{sleeping (h)} \quad (5)$$

To test the sensitivity of the Tracmor to distinguish among different levels of daily physical activity, the subjects were assigned to separate activity groups with "low," "moderate," and "high" activity levels based on their average weekly Tracmor value as well as their PAL. By dividing the ranges of the average Tracmor output and PAL into three equal sections, the activity levels were defined as follows: low, average Tracmor output < 900 and PAL < 1.60; moderate, 900 ≤ average Tracmor output ≤ 1,150 and 1.60 ≤ PAL ≤ 1.85; and high, average Tracmor output > 1,150 and PAL > 1.85.

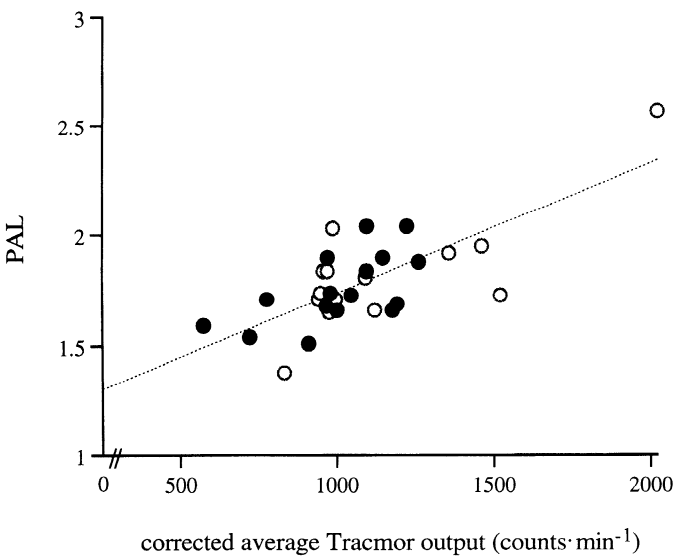

Fig. 4. Relationship between daily physical activity level (PAL = average daily metabolic rate/SMR) and average Tracmor output corrected for values > 8,000 counts/min. Separate values for men (●) and women (○) are shown. Dotted line, pooled regression line: PAL = 1.16 + 5.88 × 10^{-4} × Tracmor counts/min (n = 30; r = 0.73; SE of estimate = 0.15; $P < 0.001$).

Table 4. *Correspondence between average Tracmor output and ADMR as a multiple of SMR (PAL = ADMR/SMR) in discriminating among different levels of daily physical activity*

	Tracmor Output		
	Low	Moderate	High
PAL			
Low	4	2	0
Moderate	1	11	1
High	0	4	7

See text for values of low, moderate, and high PAL and Tracmor activity levels.

The PAL intervals covered the recommended values for daily energy intake in young adults with a low (1.55 − 1.67 × SMR), moderate (1.70 − 1.78 × SMR), or high (1.82 − 2.10 × SMR) level of daily physical activity (14, 29). The correspondence between PAL and Tracmor output is shown in Table 4. As tested with a Wilcoxon signed rank test, there was no significant difference between the methods in discriminating among the three activity levels. However, in 8 of the 30 subjects, the activity level as indicated by the Tracmor differed from that indicated by PAL. In particular, activity levels with high PAL values were relatively often characterized as moderate by using the above-mentioned intervals for Tracmor output.

DISCUSSION

The present study was performed to evaluate the use of a Tracmor motion sensor for the assessment of daily physical activity in free-living subjects. This new method was compared with ADMR and its derivatives determined with doubly labeled water. The energy estimates (ADMR − SMR) and PAL were used to reflect the metabolic cost of physical activity. (ADMR − SMR) represents the absolute value of the energy expenditure for physical activity, whereas PAL indicates the overall level of daily physical activity relative to the SMR. By using the average Tracmor output, corrected for the influence of transportation, only 22% of the variation in (ADMR − SMR) under free-living conditions could be predicted. After correction for the net individual energy expenditure per count, based on the respiration chamber measurements, 36% of the variation in (ADMR − SMR) was explained. However, a better prediction was obtained when (ADMR − SMR) was normalized for body mass (40%). The highest correlation was found for the relationship between average corrected Tracmor output and PAL (Fig. 4): 53% of the variation in PAL was explained from Tracmor output, whereas additional information on sleeping hours caused a further improvement to 63%. From Fig. 4, it will be clear that the relationship between Tracmor output and PAL is influenced by the value in the *upper right corner* of the scattergram. When data

from this subject were excluded from the results, the correlation coefficient became 0.50. However, as tested with analysis of covariance, the regression line between PAL and average Tracmor output did not change after elimination of the deviating value, and, in this sense, the extreme value confirms the established relationship.

The influence of diet-induced thermogenesis was not accounted for in the present study. Assuming this influence to be 10% of ADMR, the energy compartment (ADMR − SMR) was calculated to be reduced by 30%. Similar to ADMR, PAL was reduced by 10%. Thus only 70% of (ADMR − SMR) and 90% of PAL is explained from physical activity per se, leaving a discrepancy of 30% of (ADMR − SMR)/body mass and 37% of PAL to be unexplained from Tracmor output. At least part of this discrepancy is due to the performance of static exercise, or movement against external forces (similar to pushing or pulling), which results in an increase of energy expenditure without an (proportional) increase in the amount of body movement. Furthermore, missing information about the hours the accelerometer and data unit were not worn might have affected the prediction of the various energy estimates for physical activity. By calculating average weekly Tracmor values, it was assumed that these values represent body movement throughout the total 7-day observation period. From the activity logs, however, it appeared that the equipment was often not worn during intensive sports activities. As these activities may have a considerable impact on energy expenditure, the lack of Tracmor data during these periods might have caused an underestimation of the energy estimates. This seems to be confirmed by the underestimation of the high PAL values from Tracmor output in four subjects (Table 4). Three of these subjects reported not wearing the equipment while performing sports activities. The lack of Tracmor data during sports activities may also explain the relatively low peak values in relation to the resting values for Tracmor data during sports activities in Fig. 3. Despite this shortcoming, a considerable part of the variation in daily energy expenditure could be predicted, and it is expected that improvement of the wearing comfort of the Tracmor will improve the predictability. Moreover, given the fact that the major part of daily physical activity consists of sedentary and walking activities (1, 13) and considering the demonstrated accuracy of the Tracmor under these circumstances, the method offers promising possibilities for daily physical activity assessment.

It seems unlikely that individual differences in the relationship between body movement and energy expenditure in the present population have led to a substantial deviation between Tracmor output and energy estimates in the field study, because no such differences were found in the calibration experiments and there was only a small effect of the individual net energy expenditure per count from the respiration chamber measurements on the prediction of ADMR and (ADMR − SMR) in the field. The negligible contribution of the individual calibration factors and regression lines opens the way to studying large populations. Nevertheless, possible variation in individual relationships between body movement (Tracmor output) and its metabolic cost should be considered when comparing populations with strong variability in physical capacity and physical characteristics. The correlations between Tracmor output and energy expenditure for physical activity found during the calibration experiments of the present study correspond well with correlations from previous evaluations of the Tracmor during walking [r = 0.95 (4)] and a 1-day activity protocol in a respiration chamber [r = 0.89 (3)]. These correlations, determined under laboratory conditions, were all stronger than those found for the field experiment of the present study. The absence of above-mentioned factors like static exercise or not wearing the equipment, as well as the strictly controlled environment and/or standardized performance of activities in the laboratory experiments, largely account for the difference with the correlations found in the field experiment. In addition, the larger ranges in Tracmor output and energy expenditure in the laboratory, especially during walking (Tracmor output = 697–3,216 counts/min; EE_{act} = 79.21–327.68 W), compared with those during the field experiment (Tracmor output = 572–2,017 counts/min; ADMR − SMR = 19.84–88.66 W) might explain the higher correlations.

Compared with other evaluations of accelerometers under free-living conditions, however, the field evaluation of the Tracmor shows good results. Correlations between Tracmor output and daily energy measurements are generally stronger than those reported for associations between raw Caltrac output and energy measurements in free-living subjects [r = 0.49–0.54 (8, 18)] and similar to those reported after Caltrac readings were converted to kilocalorie values by using the age, height, body mass, and gender of subjects [r = 0.72–0.77 (5, 11)]. Recently, Matthews and Freedson (9) evaluated the use of a three-dimensional accelerometer (Tritrac) and found it similar to the Tracmor in free-living subjects. Correlations of 0.77–0.82 were found between Tritrac readings and total energy expenditure determined from physical activity logs. However, the Tritrac significantly underestimated free-living energy expenditure.

Although the data unit of the Tracmor is equipped with filters (0.11–20 Hz) to attenuate frequencies that are not produced by voluntary human movement, the average Tracmor output was significantly influenced by recordings during transportation. Vibrations produced during transportation may have frequencies within the range of human movement (16) but cannot be attenuated by a low-pass filter with a cut-off frequency < 20 Hz because this also affects the registration of body movement. Therefore, the influence of transportation was attenuated by excluding all Tracmor data with a value > 8,000 counts/min, which could be ascribed to transportation per se. In this way, some vibrations produced by transportation are still included in the Tracmor output. These vibrations, however, do not influence the relationship between Tracmor output and energy expenditure because elimination of all registration periods when the subjects were engaged in transportation did not cause any further improvement of the prediction of the various energy measures.

With respect to the discrimination among separate levels of daily physical activity, Tracmor values are not significantly different from PAL values, which are now favored by the World Health Organization (29). The intervals given for PAL cover those recommended by this organization and the National Research Council (14) to indicate daily activity levels with low, moderate, and high intensities. When Tracmor cut-offs for different activity levels were converted to PAL values by using the single factors or regression lines from the calibration experiments, the best results were obtained from the regression equation describing the association between Tracmor output and EE_{tot}/SMR during uncontrolled activity in the respiration chamber (*Eq. 4*). With the use of this equation, Tracmor cut-offs of 900 and 1,150 counts/min correspond to PAL values of 1.68 and 1.83, respectively. A major advantage of the Tracmor is the ability to measure physical activity in time, i.e., the activity pattern (Fig. 2). Therefore, the method can be used to differentiate among activity levels of separate individuals, as well as among the activity levels of one individual in time. Moreover, considering its simplicity, objectivity, social acceptability, and ease of use, the Tracmor has made a considerable contribution to the field of physical activity assessment. Calibration measurements to obtain the individual relationship between body movement and energy expenditure and activity recording in activity logs add little to the accuracy of the method, but information about the duration of sleep is required for more accurate estimations of energy expenditure. Furthermore, a reduction in the mass and size of the data unit is required to optimize wearing comfort during sports activities.

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Address for reprint requests: C. V. C. Bouten, Faculty of Mechanical Engineering, Div. of Fundamentals, Eindhoven Univ. of Technology, PO Box 513, 5600 MB Eindhoven, The Netherlands (E-mail: carlijn@wfw.wtb.tue.nl).

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