The accuracy of the Pam accelerometer in assessing daily physical activity

Siska R. Sprenger,[1] Mathieu H.G. de Greef,[1,2] Wiebren Zijlstra,[2] Theo W. Mulder[2]

Academic Center for Sports, Movement and Health
1 University Center Pro Motion, University of Groningen, The Netherlands
2 Institute for Human Movement Sciences, University of Groningen, The Netherlands

ABSTRACT

Purpose: The Pam (Physical Activity Monitor) accelerometer is a performance-based instrument to assess physical activity under free-living conditions. This study examined the validity and reliability of the Pam to estimate energy expenditure (EE) during treadmill walking and running and during outdoor walking at several speeds.

Methods: Twenty-nine adults (15 male, 14 female) performed a treadmill test and an outdoor test, both at several speeds. In all participants the Pam was attached to the right hip. EE was measured using a portable metabolic measurement system to evaluate the validity. To test the intersession reliability both tests were performed twice under the same circumstances with a one-week interval.

Results: The correlations between indirect calorimetry and Pam score ranged from r = .59 to r = .84 for the treadmill test and from r = .83 to r = .85 for the outdoor test. The correlations were higher for walking speeds > 4.8 km/h. Intersession correlations for the treadmill tests and for the outdoor tests ranged from .62–.91 and from .65–.83, respectively.

Conclusion: This study reveals a moderate-to-good validity and reliability of the Pam's estimate of energy expenditure during different walking speeds. However, we need to examine the Pam for various forms of lifestyle activities. Together with the possibility of its monitoring system, Pam might offer a good performance-based instrument to assess physical activity in large-scale use and in health-enhancing physical activity programs.

Key words: physical activity assessment, accelerometer, validity, reliability

INTRODUCTION

PA has often been described as any bodily movement produced by skeletal muscle action (6). That definition includes all forms of human motion. PA can be classified into different domains: sports activities, leisure-time physical activities, gardening and yard work, household chores, active transportation (walking, cycling) and occupational physical activities (20). To register habitual physical activity (PA), evaluate the effectiveness of behavioral interventions like the enhancement of PA and its health benefits an accurate instrument is needed.

In large scale surveys PA and energy expenditure (EE) in general have been estimated by employing questionnaires, diaries and interviews. These self-reported instruments, however, are limited because subjects have difficulties in recalling their physical activities over a certain time period, and are inclined to overestimate their physical activity, especially when lifestyle activities are involved (17,23,24,28). Hence, a novel performance-based, objective instrument for measuring PA during daily life activities is necessary.

One type of performance-based methods is a device to register physiological parameters like heart rate registration (29). The applicability to a wide-scale use for daily monitoring in free-living physical activity is limited in feasibility because it is a relatively expensive procedure when data have to be analyzed.

Another type of performance-based methods for estimating PA of large populations is a motion sensor. They seem to be a viable option for estimating PA of large populations, because they are objective, simple, lightweight and relatively inexpensive (20). Two principles exist in the measurement of PA by motion sensors (20). The first is the stepcounter principle like the pedometer, the actometer and the large scale integrator (LSI). The second principle incorporates acceleration of the movement. These more sophisticated devices are able to detect and record the actual magnitude of acceleration, allowing the amount and intensity of movements to be determined. These devices allow subjects to wear them for long time periods (10).

Most devices are developed to estimate energy expenditure during lifestyle activities, like the Caltrac (Muscle Dynamics Fitness Network, Torrance, USA), the CSA monitor (Computer Science and Applications, Inc., Shamilar, USA) and the Tritrac monitor (Hemokinetics Inc., Madison, USA). However, unequivocal data concerning the applied value of these devices is lacking until now (14,15). A recent study by Welk (2000) showed that the validity of activity monitors (CSA, Tritrac and Biotrainer) depend substantially on the context (laboratory $r = 0.85 - 0.92$ vs. field $r = 0.48 - 0.59$) and the type of activity (36). These results are in accordance with the results of other studies (2,9,10).

Another promising monitor has been developed recently: the *Personal Activity Monitor* (Pam, type AM 100, Pam B.V., the Netherlands). Pam is a small-sized unidirectional accelerometer. The direction of the sensitive axis, however, is such that the vertical and forward direction are combined. It has the ability to store data continuously for 112 days (with one-day intervals).

Like some other devices, Pam has computer-uploading capabilities through a special website. In this way, Pam users or researchers can observe the physical activity pattern of recent days/weeks. They also can use the website to specify

their physical activity goals, receive feedback and to make comparisons with existing standards of physical activity like the ACSM norms (25,32).
Pam differs from most other small-sized and easy-to-use activity monitors because it measures the acceleration in both horizontal and vertical direction whereas most existing devices this small are uniaxial. Together with the possibility of the monitoring system using a website, Pam might be a good performance-based instrument to assess PA in large-scale use. Especially for different groups sedentary persons the Pam is useful for self-monitoring in the enhancement of physical activity. The Pam website offers individuals a step by step support in realising ACSM standards of physical activity (25,32).
The purpose of this study is to determine the validity and reliability of the Pam in estimating the daily energy expenditure during treadmill walking and running, and during outdoor walking at several speeds.

METHODS

Subjects

Twenty-nine subjects out of 50 members of recreational sport groups for seniors (ranging in age from 55–65 yr, mean age: 64.2 yr) volunteered to participate in this study. Subjects with health problems or physical limitations that would prevent them from participating or that would interfere with the aim of the present study were excluded. All subjects completed a physical activity readiness questionnaire (PAR-Q) (30). Two subjects were excluded because of health problems. A written informed consent was obtained from each subject.

Instruments

The Pam AM100 is a small-sized (58x43x12 mm), lightweight (28 g) accelerometer with a piezoelectric sensor. The piezoelectric element produces a voltage in response to accelerations with a sensitivity of 2 mV/G. Its sensitive direction is 45 degrees with respect to the ground. The signal is filtered with an analogue filter and subsequently rectified and integrated by a capacitor. The capacitor voltage is digitized and zeroed every second and transferred to a storage medium and integrated over a user-specified time interval.

Metamax II (Cortex Biophysik, Germany) is a lightweight portable metabolic stress test system that has been used in a number of studies (18,19). A flexible face mask covers the subjects' mouth and nose and is attached to a flow-meter. Analysis of inspiratory and expiratory flow is done by a volume transducer, an oxygen sensor, a carbon dioxide sensor, a pressure sensor and a temperature sensor. All data measured by the Metamax II (Vt, VO_2, CO_2, RER, heart frequency, etc.) can be stored in its internal logger.

Procedures

The subjects performed a treadmill test (ENMill, Enraf Nonius, the Netherlands) in a laboratory and an outdoor walking test on 2 separate days. The treadmill test and the outdoor walking test were performed twice under the same circumstances with a one-week interval to assess intersession (test-retest) reliability. The protocol of both tests is shown in Table 1.

TABLE 1: Description of exercise protocols

	Exercise intensity/speed	**Duration (min)**
Treadmill Test	$4.0\ km \cdot h^{-1}$	2
	$4.8\ km \cdot h^{-1}$	3
	$6.4\ km \cdot h^{-1}$	3
	$7.0\ km \cdot h^{-1}$ or $8.0\ km \cdot h^{-1}$ running	3
Retest	Same protocol after one week	
Outdoor walking test*	Subjects' preferred speed	5–6
	Speed faster than track 1	4–5
	Speed faster than track 2	3.5–4
Retest	Same protocol after one week	

* For the outdoor walking test a track of 450 meters was used. Subjects started the test with the usual personal walking speed. They walked the track three times, and on every round were instructed to walk it faster than on the previous one. The *mean* walking velocity per track was assessed by measuring the time each participant needed to walk the track.

Before the test-session started length and weight of each participant were measured barefoot. The Pam was attached on the right hip and connected with a notebook computer. The Pam averaged the acceleration of the subject's body every second and transmitted the data with one-second intervals to the notebook. To determine the validity of the Pam, indirect calorimetry was employed using the Metamax II. Gas analyzers were calibrated before each test session using ambient air and two separate gas concentrations. Volume of air was calibrated using a 3-L calibration syringe. Oxygen consumption was measured with 10-s intervals during the tests and stored in the internal logger of the Metamax. The mean of the 6 intervals in each minute was used for data analysis.

Data analysis

The Pam score and oxygen uptake were converted to the same MET unit to allow for a comparison. The MET unit gives the energy expenditure of physical activity as a multiple of the basal metabolic rate (BMR) and is computed using the following formulas (derived from the equation used by Heyward, 2002) (11). These formulas have been corrected for the extra weight (5 kg) the subjects carried during the outdoor test.

1) BMR = 39.9*FM + 80*FFM + 1096 ($kJ\cdot day^{-1}$)
(FM = fat mass, FFM = fat free mass)
FFM = 4.946 – 0.066*age + 0.26*length + 0.296*weight – 10.443*sex
(male = 1; female = 2; age in years; length in cm; weight in kg)
FM = weight – FFM
To express BMR in kcal/min, divide it by (4.185 * 1440)

2) MET is calculated using the oxygen uptake measured during activity:
MET (O_2) = ((VO_2*5 – BMR) * (weight/(weight+5)) + BMR) / BMR

3) MET (Pam) = (Pam score / 100 + 1) *10 / 9

Because of the physiological adaptations that take place in the body during physical activity, it takes time before the oxygen uptake reaches the level that corresponds to the amount of exercise, whereas the Pam immediately registers a change in exercise intensity. For a proper comparison of these variables, a time shift of the oxygen uptake is needed; this has been done using only the VO_2 during steady state in the analysis, and smoothing the Pam data. Average oxygen intake of the last minute of each walking speed/track was considered to be representative for each walking speed/track.

Statistical Analysis

All analyses were performed using the Statistical Package for the Social Sciences (SPSS, version 10.1). Statistical significance was defined as $p < 0.05$. Analyses were initially performed on men and women separately and on the total group data. No gender differences were noted, so data are presented for the total group.
Analysis of variance (ANOVA with Bonferroni) was used to examine the sensitivity of Pam to changes in speed. The intersession reliability was determined using an intraclass correlation coefficient. Correlation and regression analysis were used to examine the relationship between Pam scores

and measured oxygen uptake. Bland Altman plots (statistical software MedCalc, version 7.0.1.1), (3) were constructed to show the relationship of the error score (Pam score minus oxygen uptake) across the range of intensities.

RESULTS

The characteristics of the subjects are reported in Table 2, both for the laboratory setting and the field setting.

TABLE 2: Descriptive characteristics of the subjects, mean (SD).

TREADMILL	**Men (N=14)**	**Women (N=9)**	**Total (N=23)**
Age (yr)	64.9 (3.7)	64.3 (3.4)	64.7 (3.5)
Height (cm)	177 (5.4)	166 (4.3)	172 (7.5)
Weight (kg)	81.9 (10.8)	69.2 (10.7)	77.0 (12.3)
BMI ($kg \cdot m^{-2}$)	26.2 (3.9)	25.2 (3.6)	25.8 (3.7)
OUTDOOR	**Men (N=15)**	**Women (N=14)**	**Total (N=29)**
Age (yr)	63.8 (3.1)	64.6 (3.4)	64.2 (3.2)
Height (cm)	177 (5.5)	165 (6.7)	171 (8.4)
Weight (kg)	83.0 (11.7)	73.1 (10.3)	79.7 (10.4)
BMI ($kg \cdot m^{-2}$)	26.5 (4.2)	26.7 (3.6)	26.6 (3.6)

Validity

Table 3 gives the descriptive statistics (mean + SD) and the correlations for the Pam score and indirect calorimetry for each speed during the treadmill test. Both VO_2 and Pam scores are expressed as multiples of the BMR (MET values). VO_2 (in $ml \cdot kg^{-1} \cdot min^{-1}$) values are converted to resting metabolic equivalents (METs) by dividing by 3.5 (1 MET = 3.5 ml $O_2 \cdot kg^{-1} \cdot min^{-1}$). MET estimate out of Pam score was done using the formula *Pam = (0.9*MET –1) * 100*.

TABLE 3: Descriptive statistics of Pam scores and VO_2 per epoch of the tests expressed in MET values (mean and SD).

Treadmill N = 23	**METs***	**Pam**	**VO_2**	**Pearson R** Pam - VO_2
1st speed (4.0 km · h^{-1})	3.0	4.16 (0.80)	4.72 (0.71)	.59**
2nd speed (4.8 km · h^{-1})	3.5	5.25 (0.83)	5.65 (0.67)	.74**
3rd speed (6.4 km · h^{-1})	4.0	6.68 (1.02)	6.64 (0.76)	.84**
4th speed (8.0 km · h^{-1})***	8.0	9.38 (1.52)	8.31 (1.52)	.74**
Outdoor N = 29		**Pam**	**VO_2**	**Pearson R** Pam – VO_2
1st track (5.3 km · h^{-1})		6.15 (1.26)	5.88 (.94)	.83**
2nd track (6.3 km · h^{-1})		7.19 (1.14)	7.04 (1.04)	.85**
3rd track (6.2 km · h^{-1})		7.18 (1.44)	7.80 (1.22)	.85**

* According to the Compendium of Physical Activities, Ainsworth et al. 1993
** Significant at the .01 level (2-tailed)
*** Running, N = 18

During the outdoor test the *mean* walking velocity per track was measured and these values are given in table 3. It is, however, plausible that the velocity during each track was variable. The measured MET values were consistently higher than the Compendium values for treadmill walking. The discrepancies ranged from 0.3–2.6 MET.

One-way ANOVA with Bonferroni post-hoc tests demonstrated significant different mean Pam scores at 4.0, 4.8, 6.4 and 8.0 km · h^{-1} ($p < .05$). When averaging overall speeds, the correlation coefficient between speed and Pam score was $r = .83$ ($p < .01$). The same procedure was done for the oxygen uptake. Significant differences in mean VO_2 values were demonstrated. Correlation between VO_2 and walking speed was $r = .79$ ($p < .01$). The EE estimates of the Pam were within 13% of the measured EE. The Pam seems sensitive to changes in speed.

Figure 1 shows the relationship between Pam scores and indirect calorimetry. Regression analysis shows a correlation of r = .91 (R^2 = .82) between Pam score and oxygen uptake during treadmill walking (Figure 1A). For the outdoor test a correlation of r = .87 (R^2 = .76) was found (Figure 1C). Bland Altman plots (Figures 1B and 1D) were used to illustrate the error scores (Pam score minus oxygen uptake). The 95% confidence intervals are also shown in the figure. The Bland Altman plots and Table 3 show that the Pam underestimates at 4.0 km·h $^{-1}$ and 4.8 km·h $^{-1}$ and overestimates at the faster speeds.

FIGURE 1A: Scatter plot

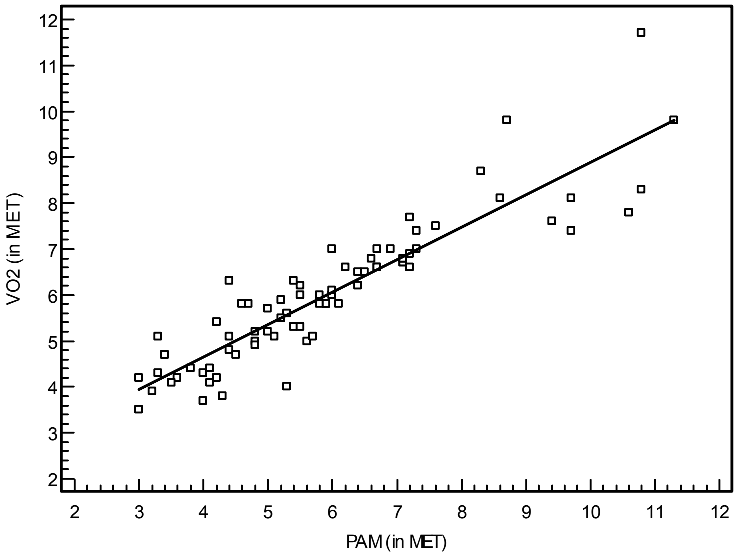

Figure 1A A Relationship between Pam score and oxygen consumption during the treadmill test. Both in MET values

FIGURE 1B: Bland Altman plot

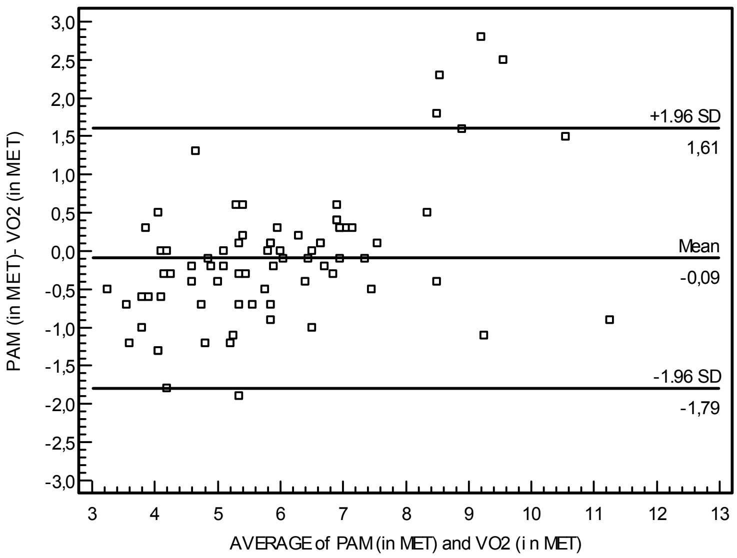

Figure 1B Bland Altman plot of Pam – O_2 during the treadmill test
Mean: -0.09. 95% Confidence Interval: -1.79 – 1.61

FIGURE 1C: Scatter plot

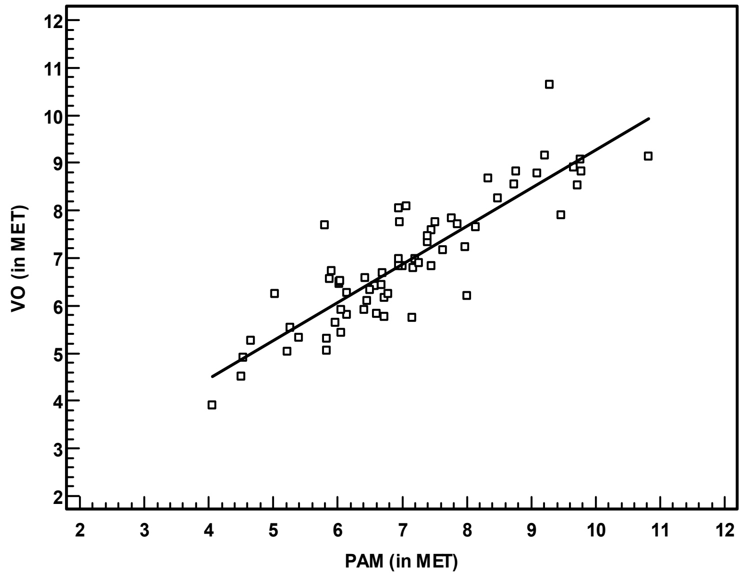

Figure 1C Relationship between Pam score and oxygen consumption during the outdoor test. Both in MET values

FIGURE 1D: Bland Altman plot

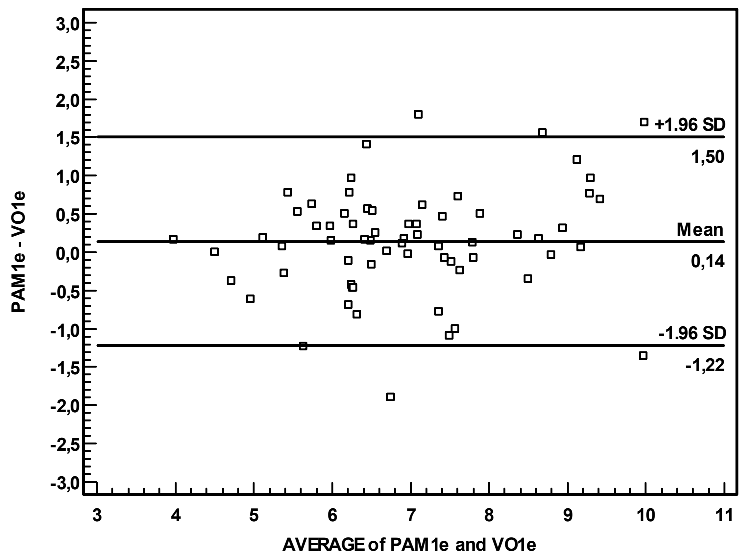

Figure 1D Bland Altman plot of Pam – O_2 during the outdoor test
Mean: 0.14. 95% Confidence Interval: -1.22 – 1.50

Reliability

Reliability coefficients are reported in Table 4. Intersession correlations for the treadmill tests and for the outdoor tests ranged from .62–.91 and from .65–.83, respectively.

TABLE 4: Intersession reliability (ICC) of the Pam for the treadmill and the outdoor tests with 95% Confidence Interval (CI),

ICC for each speed (95%CI)				
Treadmill test	4.0 km · h $^{-1}$ .68 (.33 – .87)	4.8 km · h $^{-1}$ .72 (.40 – .89)	6.4 km · h $^{-1}$ .72 (.40 – .89)	8.0 km · h $^{-1}$ .94 (.80 – .98)
Outdoor test	1st bout .77 (.57 – .89)	2nd bout .83 (.67 – .92)	3rd bout .66 (.36 – .84)	

N = 23 for the treadmill test and N = 29 for the outdoor test

DISCUSSION

Moderate-to-strong correlations between Pam scores and oxygen consumption were found for outdoor walking and treadmill walking. It seems that the correlation is stronger for intensities between 5.6 and 8.3 MET. This is also shown by the Bland Altman plots, where the difference is lowest between those intensities (Figure 1B and 1D). These results are consistent with previous studies (8,31), where moderate-to-high correlations have been found between indirect calorimetry and accelerometer data.

The intersession reliability shows moderate-to-strong correlations for treadmill walking and outdoor walking. Significant differences between mean Pam scores at the different treadmill speeds were shown by a one-way ANOVA. These results indicate that the Pam can distinguish between various intensities of walking and jogging. It can, therefore be a useful tool for assessing lifestyle activities if most movements consist of walking, jogging or relate movements of the entire body. In adults, walking is by far the most common physical activity.

We found the Pam estimating within 13% of the measured EE, where it underestimates the low intensities and overestimates the high intensities (see also Table 3). Most studies report poor predictive validity when data from activity monitors are used to predict EE (36). The tendency for the devices to overestimate EE at higher intensities is consistent with previous literature from other monitors (5,22,23,34,36). Evidence suggests that physical activity surveys may be less accurate in assessing light-to-moderate intensity activities than more vigorous activities (27,34). Also, this study shows a lower correlation between Pam score and oxygen consumption at a light-to-moderate intensity (treadmill walking at 4.0 km·h^{-1}). The reason for this could be that this group of people is not used to walking on a treadmill so that the warm-up time they had was too short. The adjustment period should have been longer, and it is possible that the 4.0 km·h^{-1} period was still experimental for these test subjects because they were not adapted to treadmill walking yet.

Another possible explanation for the inaccuracy of the Pam is the intra- and inter-individual differences in walking, both outdoors and on the treadmill. In general, not only accelerometers show individual differences, as oxygen consumption is also susceptible to individual variability. Results of the treadmill test demonstrate that differences in walking efficiency might be a cause for the variation in Pam scores between subjects at the same treadmill speed. A higher efficiency probably results in a lower Pam score, but also in a lower EE (results of oxygen consumption of a few subjects who are trained runners show this). Since the aim of the Pam is to estimate EE, the variation in Pam scores is therefore acceptable.

The attachment of the Pam to the subjects needs special attention. The output of body-fixed accelerometers results from body acceleration, gravitational acceleration and noise from sources outside the body. Hence, accelerometer output is dependent on its location on the human body, its orientation with respect to the gravitational acceleration vector, and vibrations of external sources (4). An accelerometer should be fixed firmly to the subject's body. The Pam can easily be clipped to the belt or clothes at waist level. Still, the soft tissue layer under the Pam may influence the Pam score slightly. Validity as well as intersession reliability might be affected when the Pam is not attached the same way to the subject's belt or clothes during test and retest.
A notable difference in technology among devices is the three-dimensional vs. one-dimensional activity monitors. The Pam measures acceleration in one direction, combining two directions with a sensor placed at an angle of 45 degrees, presumably estimating EE less accurately than a three-dimensional device (35). However, previous studies (36) have reported high correlations between unidirectional and three-directional devices, which suggests that the various accelerometry-based devices provide similar information despite different technologies and sensitivities. The main reason for this is that the most important contribution to the EE is caused by the vertical movements, which can be measured by one single sensor. The error made by excluding the two other directions is much smaller than the uncertainty in the estimation of the EE by accelerometry. Therefore, we do not assume that the use of a one-dimensional activity monitor is a clarification for the inaccuracy of the Pam.
Attention has to be drawn to a few results shown in table 3. The energy requirements of all walking speeds were significantly higher than values found in the Compendium (1). Other studies show similar differences (2,36). Also, the preferred walking speed is high (5.3 $km{\cdot}h^{-1}$), while a normal walking speed is between 4 and 5 $km{\cdot}h^{-1}$). This can be explained by the fact that all participants are a member of a recreational sports group and therefore have better endurance and a higher walking speed. Furthermore, the mean walking speed for track three was lower than the mean walking speed for track two, while participants were instructed to walk track 3 faster. An explanation might be the difficulty to estimate the own walking speed correctly. Moreover, it is possible the participants could not walk track three faster due to fatigue.
Pam might be useful as a feedback and monitoring system in health enhancing programs. Besides the above mentioned requirement of objectivity, an activity monitor should play a role also as an enhancer of intrinsic motivation. Indeed, most people in health-enhancing physical activity programs are extrinsically motivated. It is argued here that the measuring device should be able to deliver feedback about the actual amount of PA to the subject in order to play an additional role in changing someone's physical activity behavior (16,26,33). Moreover, the instrument should register and store the PA-data in a simple and automated way, minimizing the need for memorizing scores and for writing down the scores such as the case in activity diaries and most stepcounters. Pam provides in these needs by the ability to store data, the uploading capabilities and the website.
Despite the benefits of accelerometers, these methods used for the estimates of PA are limited in accuracy and reliability. This applies particularly in relation to non-ambulatory physical activity, which is very difficult to detect by motion sensors. Furthermore, motion sensors require a placement on the body which

prevents underestimation or overestimation of the physical activity. Placing the accelerometer on the waist gives an accurate estimate of the energy expenditure of the whole body during walking patterns (37). Much of the error is due to the inability of a waist-mounted accelerometer to detect arm movements as well as activities such as carrying weights, walking uphill or stair-climbing (2,10,20). Consequently, for some physical activities the Pam does not give an accurate estimate (e.g. bicycle riding, swimming, fitness, skating). A few studies have been performed on assessing energy expenditure by an activity monitor during bicycle riding. Results of a study by Iltis and Givens (2000) suggest that the Caltrac is inaccurate for assessing caloric cost of cycling, as it underestimates energy expenditure at every load (13). While riding a bike is a very common physical activity in the Netherlands, further research is needed to investigate the Pam estimate of EE during this activity.

Overall, this study reveals a moderate-to-good validity and reliability of the Pam's estimate of energy expenditure during different walking speeds. However, it is necessary to examine the Pam for various other forms of lifestyle activities. It is important to have accurate estimates of the EE in free-living situations. Together with the possibility of its monitoring system, Pam might offer a good performance-based instrument to assess PA in large-scale use and in health-enhancing physical activity programs.

ACKNOWLEDGMENTS

This work was supported in part by grants from the Dutch public health fund OGZ (P 265). The opinions expressed herein are those of the authors and do not necessarily represent the views of OGZ. The use of the trade names and commercial sources is for purposes of identification only and does not imply endorsement.
Address for correspondence: S. R. Sprenger, Academic Center for Sports, Movement and Health, University Center Pro Motion, L.J. Zielstraweg 1 9713 GX Groningen, The Netherlands, E-mail: S.Sprenger@med.rug.nl, Tel: +31 (0)50 3632541, fax: +31 (0)50 3183345

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