Evaluation of methods to assess physical activity in free-living conditions

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ABSTRACT

LEENDERS, N. Y. J. M., W. M. SHERMAN, H. N. NAGARAJA, and C. L. KIEN. Evaluation of methods to assess physical activity in free-living conditions. *Med. Sci. Sports Exerc.*, Vol. 33, No. 7, 2001, pp. 1233–1240. **Purpose:** The purpose of this study was to compare different methods of measuring physical activity (PA) in women by the doubly labeled water method (DLW). **Methods:** Thirteen subjects participated in a 7-d protocol during which total daily energy expenditure (TDEE) was measured with DLW. Body composition, basal metabolic rate (BMR), and peak oxygen consumption were also measured. Physical activity-related energy expenditure (PAEE) was then calculated by subtracting measured BMR and the estimated thermic effect of food from TDEE. Simultaneously, over the 7 d, PA was assessed via a 7-d Physical Activity Recall questionnaire (PAR), and subjects wore secured at the waist, a Tritrac-R3D (Madison, WI), a Computer Science Application Inc. activity monitor (CSA; Shalimar, FL), and a Yamax Digi Walker-500® (Tokyo, Japan). Pearson-product moment correlations were calculated to determine the relationships among the different methods for estimating PAEE. Paired *t*-tests with appropriate adjustments were used to compare the different methods with DLW-PAEE. **Results:** There was no significant difference between PAEE determined from PAR and DLW. The differences between the two methods ranged from −633 to 280 $kcal \cdot d^{-1}$. Compared with DLW, PAEE determined from CSA, Tritrac, and Yamax was significantly underestimated by 59% (−495 $kcal \cdot d^{-1}$), 35% (−320 $kcal \cdot d^{-1}$) and 59% (−497 $kcal \cdot d^{-1}$), respectively. $\dot{V}O_{2peak}$ explained 43% of the variation in DLW-PAEE. **Conclusion:** Although the group average for PAR-PAEE agreed with DLW-PAEE, there were differences in the methods among the subjects. PAEE determined by Tritrac, CSA, and Yamax significantly underestimate free-living PAEE in women. **Key Words:** ACCELEROMETER, STEPCOUNTING, INTERVIEW, DOUBLY-LABELED WATER, WOMEN

Regular physical activity (PA) is important during all stages of life. Activity producing daily energy expenditure of 150 $kcal \cdot d^{-1}$ or 1000 $kcal \cdot wk^{-1}$ has substantial health benefits (29). This amount of PA can be obtained in a variety of ways and the activity does not necessarily have to be vigorous. When evaluating PA and its patterns, it is important that different levels of PA and associated energy expenditure be measured accurately. Accurate assessment of PA, specifically the energy expenditure associated with that PA in free-living conditions, is difficult (7,27).

The assessment of PA in free-living conditions has been performed using techniques such as retrospective questionnaires, activity diaries, physiological measurements via mechanical and electronic instrumentation, and the doubly labeled water method (DLW) (14). The majority of these methods produce data that can be converted to total daily energy expenditure (TDEE) or physical activity-related energy expenditure (PAEE).

TDEE has three components: 1) resting metabolic rate (RMR); 2) thermic effect of food (TEF); and 3) PAEE (24). Under most circumstances, 10–15% of TDEE is due to TEF (20) and 60–65% is due to RMR (16). For individuals aged 17 and older, only 50% of the variation in TDEE is explained by RMR (11). This indicates that interindividual variation in TDEE is mostly due to PAEE. It is this component of TDEE that is associated with substantial health benefits. Thus, for intervention studies and for epidemiological studies, it is necessary to measure PAEE as accurately as possible.

DLW can be used to measure TDEE over a period of time in individuals under free-living conditions (14). With this technique, PAEE can be determined indirectly by subtracting RMR and TEM from TDEE. Due to the high cost of the isotopes, and the cost and complexity of analysis with gas isotope-ratio mass spectroscopy, there is limited applicability of the DLW to large populations. This technique is often used as the criterion method to evaluate other instruments for determining TDEE and PAEE (4,14).

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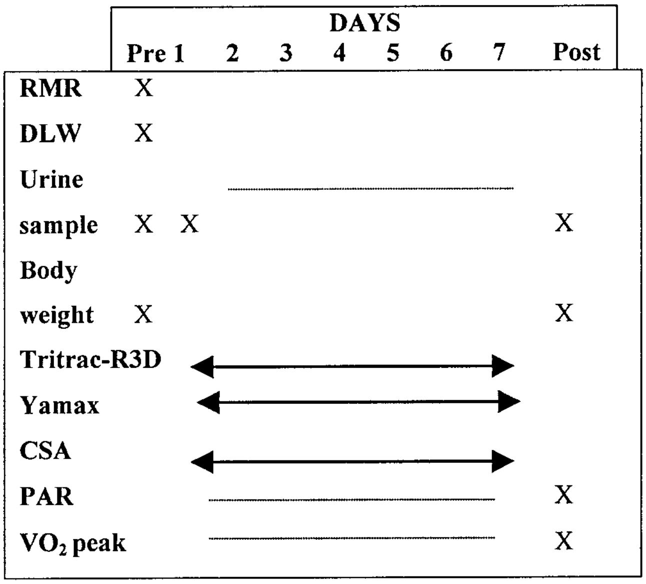

FIGURE 1—Experimental protocol; CSA, Computer Science and Application Inc. monitor; PAR, 7-d Physical Activity Recall interview; RMR, resting metabolic rate; DLW, doubly labeled water.

The purpose of this study was to determine the accuracy of methods that measure PA and associated energy expenditure in women in free-living conditions. The following methods were used to measure PAEE: 1) DLW for TDEE and indirect calorimetry for RMR; 2) the 7-d Physical Activity Recall questionnaire (PAR); 3) the Tritrac accelerometer that registers body accelerations in three planes; 4) a Computer Science and Applications Inc. monitor that measures body accelerations in one plane (CSA); and 5) a Yamax-Digiwalker-500® that registers steps. The PAR was chosen because it is widely used and from self-report provides an estimate of PA associated energy expenditure. Walking, aerobics, and aerobic dancing are the most commonly reported leisure-time physical activities for women (29). Thus, the Tritrac, CSA, and Yamax were used because they can easily assess bodily movement associated with these types of activities. These instruments have gained popularity and have been used in intervention studies to evaluate the effect of a PA program on health-related outcomes. The PAR has been validated with DLW in obese women and adult men (15,17), but neither the Tritrac, CSA, nor Yamax has been evaluated against DLW in women.

METHODS

Subjects

Thirteen healthy women participated in a 7-d experimental protocol (Fig. 1). Subjects were required to meet the following criteria to be eligible for the study: a) normal health status and no evidence of heart disease, diabetes, hypertension, or other chronic diseases as determined by a medical history and physical examination; b) no evidence of current pregnancy; and c) normal menstrual history and a nonuser of oral contraceptives. After the experimental protocol was explained, each subject signed an informed consent statement approved by The Ohio State University Biomedical Sciences Human Subjects Review Committee.

Subjects wore the activity monitors for 7 d before the start of the 7-d period and were asked about their PA pattern with the PAR interview (data not presented). The reason for data collection before the7-d experiment was to ensure that: 1) the PA pattern was primarily ambulatory, i.e., they did not participate in any type of weight-training, cycling, or water activities; this selection criteria was required because the accelerometers and step-counter are devices primarily designed to assess bodily movement (accelerations) primarily during ambulatory activity; 2) they exhibited a wide range of PA, i.e., from low (no or little reported PA) to high (meeting or exceeding the current PA recommendations); and 3) they were familiar with the appropriate wearing of the instruments.

Experimental Protocol

The experimental protocol lasted 7-d and started with an overnight stay at the General Clinical Research Center (GCRC; Fig. 1). Subjects consumed the determined DLW dose in the evening and RMR was measured the following morning. Energy expenditure determined by DLW was assessed over the 7-d experimental period. During all waking hours in this 7-d period, subjects wore a Tritrac-R3D accelerometer (Professional Products Reining Int., Madison, WI), a Computer Science Applications, Inc. activity monitor (CSA; Model 7164, Shalimar, FL), and a Yamax Digi-Walker-500® (Yamax Corporation, Tokyo, Japan). These instruments were secured at the waist and attached to a belt. After 7 d, subjects returned to the laboratory to respond to the PAR. Body composition via hydrostatic weighting was measured before and after the start of the 7-d period. Peak oxygen consumption was measured during treadmill testing within 4 wk after the 7-d experimental period.

Physical Activity Assessment

DLW and indirect calorimetry. Energy expenditure determined by DLW was assessed over the 7-d experimental period. RMR was measured to calculate PAEE using the following formula: PAEE $=$ TDEE $-$ [(TDEE $\times$ 0.10) $-$ RMR], where TDEE $\times$ 0.10 is equated to the assumed TEF (20). Because RMR may be influenced by the phase of the menstrual cycle, the start of the 7-d period was always within 5–10 d after the onset of menstruation.

Before the start of the 7-d period, subjects reported to the GCRC at 1600 h and were given a medical examination by a physician. At approximately 2100 h, subjects were familiarized with the metabolic measurements (see below) for a period of 15 min. Thereafter, between 2130 and 2200 h, a baseline urine sample (10-mL) was obtained from all subjects. At 2200 h, subjects ingested a well-mixed solution containing a measured dose of DLW (approximately 1.5 $g \cdot kg^{-1}$ of body weight). The solution contained 10% enriched $H_2{}^{18}O$ and 99.9% enriched ^2H_2O (Cambridge Isotope Laboratories, Cambridge, MA) mixed in a 20:1 ratio. A 1:400 dilution of the stock solution was mixed together with tap water and was stored in a 10-mL Venoject vacutainer (Benton Dickinson, Rutherford, NJ). The tap water diluted tracer was analyzed to verify enrichment. The following morning, subjects were awakened at 0530 h to empty their bladder. Subjects returned to bed for the measurement of RMR. At approximately 0615 h while the subject rested in a supine posture and was awake but motionless, a canopy was placed over the subject's head. Metabolic measurements were obtained with a Deltatrac™ Metabolic Monitor (MBM-100, SensorMedics Corporation, Yorba Linda, CA) for a period of 45–50 min. The metabolic system was calibrated before each test with known verified standard calibration gases. An average of eight 10-min intervals was used for the calculation of RMR (CV $< 4.5\%$) using equation 12 from de Weir (30). After the measurement of RMR, at approximately 0800 h, subjects provided a urine sample (second void) that was used for isotopic analysis. Urine samples were stored in sterile vacutainers and kept on ice until transferred into 10-mL evacuated tubes. After 7 d, subjects returned to the laboratory at approximately 0800 h to provide a second void urine sample. This sample was used for isotopic analysis. All urine samples were stored at $-80°C$ until analysis.

Samples were analyzed in triplicate for oxygen-18 and deuterium by isotope ratio mass spectrometry at The Energy Metabolism Research Unit in the Department of Nutrition Sciences at the University of Alabama at Birmingham. The facility uses a VG Optima Isotope Ratio Mass Spectrometer (VG Isochrom-uG. Fisons Instruments Inc. Beverly, MA (10)). Carbon dioxide production (r_{CO2}; moles per day) was determined using equation 2 from Speakman et al. (26). Based upon each subject's macronutrient intake calculated from a 3-d dietary record, the energy equivalent of CO_2 was calculated, from which the food quotient (FQ) was calculated (6). The mean FQ was then used to convert CO_2 production to energy expenditure (kcal per day) using equation 12 from de Weir (30).

Activity Monitors

Triaxial accelerometer. The Tritrac ($11.1 \times 6.7 \times 3.2$ cm, 170 g) is a triaxial accelerometer that has three piezoceramic elements orthogonally mounted. When the Tritrac is attached to the body, it measures acceleration in the anterior-posterior (x), medio-lateral (y), and vertical (z) directions and summarizes that information as a vector magnitude (*Vmag*). The *Vmag* is the square-root of the sum of the squared accelerations of each direction. BMR is calculated taking into consideration the subject's age (yr), height (ht), weight (wt), and gender. For women the formula used is: $\text{kcal}\cdot\text{min}^{-1} = (0.00331 \times \text{wt (kg)}) + (0.00352 \times \text{ht (cm)}) - (0.00353 \times \text{age (yr)}) + 0.49854$. Physical activity-related energy expenditure (PAEE) is calculated by converting the *Vmag* data into energy expenditure by using the manufacturer's proprietary equations. The Tritrac was initialized to collect data at 1-min intervals. Minute-by-minute energy expenditures were reduced to an average for each day. The daily averages across the 7-d period were then summed. The average of the summed daily values was used in the statistical analysis.

Uniaxial accelerometer. The CSA activity monitor ($5.1 \times 4.1 \times 1.5$ cm, 43 g) is a uniaxial accelerometer that measures acceleration only in the vertical direction (z). The monitor is designed to detect acceleration ranging in magnitude from 0.05 to 2.0 G with a frequency response between 0.25 and 2.5 Hz. These frequencies were chosen to eliminate recording of accelerations when the frequency of the acceleration is outside the frequency range of the acceleration of the human body. The CSA contains a microprocessor that digitizes the filtered acceleration signals, converts the signal to a numeric value, and accumulates this value as activity counts over a selected time interval. At the end of the time interval, the activity counts are stored and the accumulator resets itself to zero. The activity monitor was initialized with a time stamp and a 1-min data collection time interval. PAEE was calculated from activity counts using the following formula: $\text{kcal}\cdot\text{min}^{-1} = (0.00094 \times \text{cts}\cdot\text{min}^{-1}) + (0.1346 \times \text{mass (kg)}) - 7.37418$ (8). Minute-by-minute energy expenditures were reduced to an average for each day. The daily averages across the 7-d period were then summed. The average of the summed daily values was used in the statistical analysis.

Pedometry. The Yamax-Digiwalker-500® is an electronic pedometer that operates on a horizontal, spring-suspended lever arm that moves up and down with vertical accelerations of the hip. With each step, the lever arm makes an electrical contact, and one step is recorded. When body mass is entered into the pedometer microprocessor, caloric expenditure is estimated by the manufacturer's proprietary regression equation. The daily energy expenditures and steps taken were summed and divided by seven to estimate daily energy expenditure from the Yamax. This was used in the statistical analysis.

The Tritrac and CSA were placed in a pouch ($15.5 \times 12.5 \times 4$ cm; Eagle Creek, San Marcos, CA) or nylon pocket (supplied by the company), respectively. These were attached to a belt that was worn by the subjects to minimize the recording of extraneous movements not due to PA. The Tritrac and CSA were positioned over the right and left hips, respectively. These positions were chosen to ensure that the attachment of the accelerometers to the body did not interfere with the subjects' pattern of daily activity. The Yamax was clipped on the belt on the right side of the body along the anterior mid-line of the thigh. Subjects were instructed on precise positioning of the Tritrac, CSA, and Yamax. Because the Yamax does not record the steps using an internal time stamp the displayed number of steps taken and calories expended was recorded by the subjects at the end of the day, just before going to bed. Each morning the subjects pushed the reset button to zero.

Subjects returned to the laboratory after 7 d to return the Tritrac, CSA, and the Yamax. During this visit, subjects were interviewed for the PAR.

7-d Physical Activity Recall. The PAR was conducted using a standardized interview format (19), and the same interviewer conducted all interviews. During the interview, subjects were asked to estimate the number of hours during each of the previous 7 d that were spent in sleep and moderate, hard, and very-hard intensity PA. The hours engaged in each of these categories were then summed. The remaining hours left in the 7-d period were determined to be spent in light intensity activity. Standardized values of energy expenditure were assigned to the various activities (19). Sleep, light, moderate, hard, and very hard activities were categorized as 1.0, 1.5, 4, 6, and 10 METs, respectively, where one MET was equivalent to 1 $kcal \cdot kg^{-1} \cdot h^{-1}$ (1). MET values were then multiplied by hours spent in each of the categories to estimate PAEE as $kcal \cdot d^{-1}$. The sum of the 7 d of energy expenditure was then divided by seven to obtain the daily average PAEE.

Peak oxygen consumption. $\dot{V}O_{2peak}$ was measured after the end of the 7-d period at least 2 h postprandial in a thermoneutral environment. Subjects avoided strenuous PA on the day before the test. After arrival in the laboratory, the subjects rested for a minimum of 20 min. Before measuring metabolic rate, the oxygen and carbon dioxide analyzers were calibrated with verified standard calibration gases. Volume was calibrated with a 3-L syringe (Hans Rudolph, Kansas City, MO). Expired air was analyzed via a Med Graphics-CPX-D metabolic cart (Medical Graphics, Minneapolis, MN). Subjects underwent a maximal treadmill test to determine $\dot{V}O_{2peak}$ by using the Bruce protocol.

Body composition. Body mass, percent body fat, and lean body mass were determined by hydrostatic weighing 1 d before and 1 d after the 7-d period. Each subject's body mass was measured on land and while totally submerged in water (± 1 g). Body density was calculated taking into account residual volume that was measured by the oxygen-dilution technique. Hydrostatic weighing and residual volume measurements were repeated until the coefficient of variation was ≤ 5%. From the calculated body density, the percentage of body mass that is fat was calculated using the Siri equation (25).

Data Analysis

Descriptive statistics were used to summarize the data. Because health-related benefits are associated with PA, data were analyzed for PAEE and not for total daily energy expenditure. The output from the Tritrac, CSA, and Yamax are expressed as PAEE ($kcal \cdot d^{-1}$), $counts \cdot d^{-1}$ (Tritrac-*Vmag*, Tritrac-Z, and CSA), and $steps \cdot d^{-1}$ (Yamax).

Data were analyzed in the following ways: 1) Pearson product-moment correlation (r) was used to determine the relationships among DLW and the other methods to measure PAEE; 2) differences in PAEE between DLW and each other method was determined with paired a *t*-tests incorporating Bonferroni adjustments; an analysis of variance was not utilized because the variance for the DLW data was significantly larger compared with the other methods; and 3) the differences were plotted against DLW values and linear regression analysis was performed. Statistical significance for the regression analysis was set *a priori* at $P \leq 0.05$. The SAS-JMP (SAS Institute Inc., Cary, NC) statistical package was used to analyze the data. Data are presented as mean ± SEM.

TABLE 1. Physical characteristics of the subjects.

	Mean ± SE	Range
Age (yr)	25.8 ± 1.6	21–37
Height (cm)	166.9 ± 1.5	155.0–175.3
Body mass pre (kg)	65.5 ± 2.0	56.0–77.9
Body fat (%)	26.3 ± 1.7	12.8–37.5
Body Mass Index ($kg \cdot m^2$)	23.5 ± 0.6	19.9–27.7
DLW-TDEE ($kcal \cdot d^{-1}$)	2371 ± 110	1665–2814
RMR ($kcal \cdot d^{-1}$)	1336 ± 38	1159–1576
$\dot{V}O_{2peak}$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	42.2 ± 2.1	31.5–58.4
$\dot{V}O_{2peak}$ ($L \cdot min^{-1}$)	2.78 ± 0.11	1.96–3.36

DLW, doubly labeled water; TDEE, total daily energy expenditure; RMR, resting metabolic rate; $\dot{V}O_{2peak}$, maximal aerobic power.

RESULTS

Descriptive Results

Descriptive characteristics for the subjects are presented in Table 1. For two subjects, body mass data measured after the 7-d period was not available. Data from the remaining 11 subjects revealed that the subjects were in energy balance during the 7-d period. This is reflected by the fact that there was no significant difference in body mass measured 1 d before and 1 d after the 7-d period, 0.00 ± 0.24 kg. DLW-PAEE accounted for 33% of TDEE. Subjects wore the monitors on average 13.5 ± 0.2-$h \cdot d^{-1}$. From the PAR, it was calculated that the subjects slept on average 8 $h \cdot d^{-1}$. Thus, subjects wore the monitors approximately 75–85% of their waking hours. From the PAR, it was apparent that the subjects' participated primarily in ambulatory activities during the 7-d period. For one subject, activity counts from the CSA were not available for all 7-d; therefore, data from the CSA are presented for 12 subjects.

The 7-d average for PAEE from DLW, PAR, Tritrac, CSA, and Yamax are presented in Table 2. The correlations between PAEE estimated from the PAR, Tritrac, CSA, and Yamax and from DLW ranged from 0.42 to 0.55 ($P > 0.05$).

Paired *t*-test revealed no significant difference between PAEE estimated from the PAR and DLW (Table 2). PAEE determined from Tritrac, CSA, and Yamax significantly underestimated DLW by 35, 59, and 59%, respectively (Fig. 2, Table 3). The linear regression analysis demonstrated that the difference between PAR and DLW varied from the mean difference and was linearly related to the DLW-PAEE value (Fig. 3). Both slope and intercept were significant different

TABLE 2. Mean values for physical activity related energy expenditure.

PAEE ($kcal \cdot d^{-1}$)	Mean ± SE	Range
DLW	798 ± 83	340–1313
PAR	642 ± 35	444–930
Tritrac	478 ± 51*	263–825
CSA	330 ± 44*	61–543
Yamax	301 ± 36*	114–519

PAEE, physical activity related energy expenditure; DLW, the doubly labeled water method; PAR, the 7-d Physical Activity Recall method; Tritrac (triaxial accelerometer); CSA, Computer Science and Application Inc. monitor (uniaxial accelerometer); Yamax (stepcounter).
* $P < 0.05$ compared with DLW.

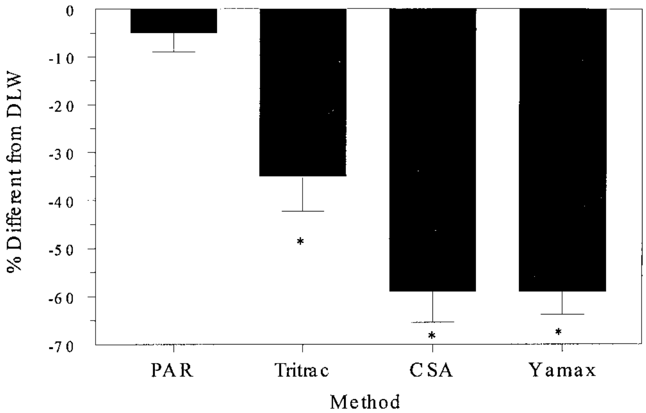

FIGURE 2—Percent difference from the doubly labeled water method (DLW), the 7-d Physical Activity Recall method (PAR), the Tritrac, CSA, and the Yamax between physical activity-related energy expenditure. Values are mean ± SEM; * $P < 0.05$ compared with DLW.

from zero ($P < 0.0001$). The differences between the two methods ranged from −633 to 280 kcal·d^{-1} (Table 3).

Bodily movement measured with the Tritrac, CSA, and Yamax explained between 18 and 30% of the variation in DLW-PAEE. The correlations ($P > 0.05$) between DLW-PAEE and Tritrac-*Vmag* (r = 0.54) and z-direction were r = 0.54 and r = 0.52, respectively. The raw activity counts (cts·d^{-1}) of the CSA and between DLW-PAEE versus steps (steps·d^{-1}) were r = 0.45 and r = 0.42, respectively ($P > 0.05$).

Physical activity-related energy expenditure measured by DLW was significantly correlated with $\dot{V}O_{2peak}$ (mL·kg^{-1}·min^{-1}) (r = 0.66, rmse = 6.0 kcal·kg^{-1}·d^{-1}). $\dot{V}O_{2peak}$ explained 43% of the variation in DLW-PAEE. Multiple regression analyses revealed that none of the other variables measured with the PAR, Tritrac, CSA, and Yamax contributed significantly to the amount of variation explained with $\dot{V}O_{2peak}$ in DLW-PAEE.

DISCUSSION

In the present study, four methods that measure PAEE were compared with DLW-PAEE. Three of these methods measured PAEE by determining bodily movement either accelerations or steps, and one method measured PAEE using an interview-recall technique. An understanding of the accuracy of these methods is necessary to use them before they can be employed appropriately in initiatives designed to measure PAEE or to measure changes in PAEE by using PA behavior change strategies. The results indicate that the Tritrac, CSA, and Yamax significantly underestimate free-living PAEE determined with DLW in women. There was no significant difference in mean PAEE measured with DLW and PAR; however, individual differences existed as a function of PA level (Fig. 3). Physical activity-related energy expenditure determined by DLW accounted for 20–47% of TDEE, indicating large interindividual variations in PA behavior among the subjects. These interindividual variations in PAEE made it possible to compare the different methods across a range of PAEE.

TABLE 3. Differences in average physical activity related energy expenditure.

	PAEE (kcal·d^{-1})	
	Mean Difference with DLW	Range
PAR	−156	−633 to 280
Tritrac	−320	−780 to 89
CSA	−495	−824 to 5
Yamax	−497	−961 to −106

PAEE, physical activity related energy expenditure; DLW, the doubly labeled water method; PAR, the 7-d Physical Activity Recall method; Tritrac (triaxial accelerometer); CSA, Computer Science and Application Inc. monitor (uniaxial accelerometer); Yamax (stepcounter).

7-d Physical Activity Recall

The PAR is a relatively easy method to use to obtain information about a person's PA behavior over the past 7-d. It requires about 15 min to conduct the interview and to compile the information about the subject's intensity and frequency of PA. The objective is to use this information to estimate energy expenditure associated with that PA. The method has been used extensively. Despite its popularity, its accuracy for determining PAEE has only been compared with DLW twice (15,17).

The results of this study demonstrate that the group estimate for PAR was not different from the group estimate of DLW. The range in the differences between the two methods was 913 kcal·d^{-1}. For the single measurement of PAEE for an individual, there were differences between the two methods. This indicates that PAR may not accurately estimate absolute PAEE for an individual. Considering same subjects' differences in PAEE between the two methods, when DLW-PAEE was less than 500 kcal·d^{-1}, PAR overestimated PAEE on average 137 kcal·d^{-1} (Fig. 3). When DLW-PAEE was above 500 kcal·d^{-1}, the PAR underestimated PAEE from DLW on average 287 kcal·d^{-1} (Fig. 3). The large over- and under-estimations by the least or most active subjects maybe due to underreporting of physical activity that is of moderate intensity.

The results of this study are not unlike the variation in accuracy of the PAR compared with DLW in 14 obese women (17). In that study after the authors adjusted the assigned MET values for PAR as a function of BMR and body mass, the difference between DLW and the PAR for PAEE during one 7-d period was 36 ± 71% and during a second 7-d period 16 ± 42%. It appears that at lower energy expenditures there was an overestimation of the PAR-PAEE compared with DLW-PAEE. It was not determined whether this was consistent or random error.

Starling et al. (27) compared several methods to assess PA with DLW in an elderly population. Although they did not use PAR, they used two measures of self-reported PA, the Minnesota Leisure Time Activity Physical Activity Questionnaire (LTA), and the Yale Physical Activity Survey (YPAS). Although PAEE from LTA underestimated DLW across the PAEE spectrum upon inspection of the results, it is apparent that the higher the DLW-PAEE, the greater the underestimation of PAEE for both women and men. The results for the YPAS versus DLW-PAEE appear to

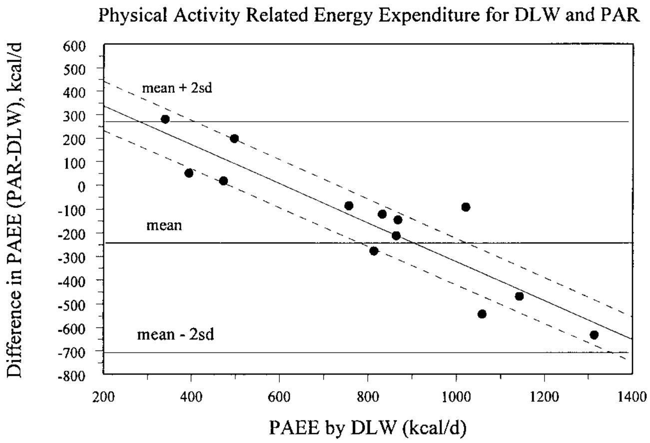

FIGURE 3—Difference between average physical activity related energy expenditure (PAEE) for the doubly labeled water method (DLW) and the 7-d Physical Activity Recall method (PAR). Each ● represents an energy expenditure value; the *middle horizontal line* reflects the mean difference between the two methods. The *solid line* is the line of the best fit representing the regression equation, and the *dashed lines* represent the 95% confidence limits about the mean differences between the two methods. $Y = 501–0.824 \cdot DLW$; $r = -0.91$; rmse = 119 kcal·d^{-1}; $P < 0.0001$.

demonstrate an underestimation of PAEE at higher levels of PAEE. The results in the current study together with these studies (17,27) suggest that an under- and overestimation of self-report PA may be directly related to the levels of PA (e.g., overestimation at low PAEE levels and underestimation at high PAEE levels). (See Fig. 3.)

Accelerometers

The group means for PAEE from the Tritrac and CSA were significantly lower by 35% and 59%, respectively, compared with DLW. Regardless of which accelerometer and which formula was used to convert body acceleration to energy expenditure, PAEE from these instruments was significantly lower compared with DLW-PAEE. Part of the underestimation of PAEE by the Tritrac and CSA may be explained by the fact that both devices are designed to register bodily movements during ambulatory activities and do not directly assess the energy expenditure associated with that movement. In fact, the Tritrac can be used to estimate energy expenditure only via the prediction equations provided by the manufacturer. This equation is proprietary and has not been validated in free-living conditions in the literature for subjects. Under controlled laboratory conditions, the estimation of energy expenditure by the Tritrac has been shown to result in under- (13) and overestimation (Leenders et al., in review) and in similar estimates of energy expenditure (23) compared with indirect calorimetry. These conflicting results indicate that even under highly controlled conditions, the estimation of energy expenditure with the Tritrac may be either inconsistent, inaccurate, or highly dependent upon the activity and the population under study. The results of this study indicate the manufacturer's equation produces a significant underestimation of PAEE. Thus, one may choose to use the Tritrac to measure bodily movement only and not the energy expenditure in free-living conditions.

The CSA activity monitor has not been compared with the DLW method in free-living conditions. The fact that the CSA can be used to estimate energy expenditure is due to a formula derived from activity counts and body mass developed under laboratory conditions (8). In that study, energy expenditure during walking, jogging, or running on a treadmill could be accurately predicted with this formula. Results from the present study indicate that the use of this prediction model in free-living conditions, for which there were different patterns of PA being performed, results in a significant underestimation of PAEE with the CSA. This may suggest there are differences among CSA instruments or differences in determination of PAEE by indirect calorimetry and DLW.

Part of the underestimation of energy expenditure from body movement might also be related to the fact that for activities that involve static exercise (carrying a load, bicycling, or walking into a head-wind), accelerometer output is not proportional to the increase in energy expenditure. None of the subjects participated in any type of weightlifting or bicycling, but in a free-living environment, carrying loads such as book bags or groceries might contribute to the underestimation of PAEE (3). When climbing stairs, the body is not accelerated in proportion to energy expenditure, and measurements of body accelerations will underestimate energy expenditure (22). Earlier research demonstrated that accelerometers do not detect the increase in energy expenditure associated with an increase in the grade of walking. The amount of stair climbing by subjects in this study was not assessed, and this may contribute to this underestimation of PAEE. Compliance of wearing the activity monitors in this study was good. From the subjects' log, it was observed that the monitors were worn during the majority of the day (≥13 h). However, there was always some discrepancy between sleeping and the wakening hours and time that the monitors were worn. Thus, during some of the time that the subjects were awake and moved, there was no registration of body movement. It is likely this produced some amount of underestimation of PAEE. For example, from the PAR it was determined that subjects slept on average 8 h·d^{-1}. Thus, if a subject performed some light to moderate intensity PA during the 2-h period per day the monitors were not worn, PAEE could have been underestimated by approximately by 100–150 kcal·d^{-1}. The only way this can be controlled for, however, is if subjects were known to wear the accelerometers all day or perhaps if the monitors were permanently attached to the subject. Because fidgeting can contribute up to 800 kcal·d^{-1} to TDEE, it is possible this movement and the associated energy expenditure are not detected by an accelerometer worn at the waist (18). Only 20% and 29% of the variance in DLW-PAEE could be explained by activity counts from the CSA and Tritrac. Thus, these accelerometers are not accurately detecting all movement-associated energy expenditure and are also not accurately estimating energy expenditure using standardized equations.

Because the Tritrac and CSA have not been evaluated with the DLW method in free-living conditions, comparisons with other studies is not possible. In fact, few studies have validated accelerometer output from a triaxial accelerometer with DLW in humans under free-living conditions. Bouten et al. (3) reported that the proportion of variance in PAEE·kg^{-1} that was explained by activity counts was 40% (r = 0.63, SEE = 4.1 kcal·kg^{-1}·d^{-1}). These authors demonstrated that when subjects walked on a treadmill, 98% of the variance in PAEE (derived from indirect calorimetry with sleeping metabolic rate subtracted) was explained by accelerometer output from their triaxial accelerometer. When these same subjects were confined in a respiration chamber for 24 h and allowed to move freely, 79% of the variance in PAEE was explained by the triaxial accelerometer. In addition, Chen and Sun (5) demonstrated that the Tritrac significantly underestimated PAEE by 52% compared with energy expenditure measured in a whole-room indirect calorimeter. Comparison of these experiments (3,5) with the present study illustrates that when a controlled environment is removed, it is very difficult to predict PAEE from body movement registered at the waist. The energy cost of bodily movement in free-living conditions is obviously difficult to quantify.

Because humans under free-living conditions exhibit multidirectional movement, it has been suggested that a triaxial accelerometer is a better monitor for the registration of body movement, and hence the estimation of energy expenditure, than a uniaxial accelerometer (3,7). The Tritrac and CSA are triaxial and uniaxial accelerometers, respectively. Although the Tritrac's estimation of PAEE compared with DLW was slightly better compared with the CSA, the underestimation of PAEE compared with DLW-PAEE by both accelerometers was still very large. Each accelerometer's detected PAEE correlated very well with each other (r = 0.77, data not shown). The amount of variance in DLW-PAEE that was explained by raw activity counts from the Tritrac and CSA were 29% and 20%, respectively. These results do not indicate that the triaxial accelerometer can detect more bodily movement than the uniaxial accelerometer. Because the Tritrac is larger in size and more expensive compared with the CSA, the benefits of the slightly improved "accuracy" of the Tritrac would have to be weighed against the practicality of its cost and convenience.

Pedometry

In the present study, PAEE estimated from number of footsteps taken per day underestimated DLW-PAEE by 59%. Because steps do not reflect the intensity of movement, they may not provide an accurate estimate of PAEE. Furthermore, average number of steps·d^{-1} explained only a small proportion of the variance in DLW-PAEE (18%). Thus, recording number of steps may not be a good reflection of absolute PA level and related energy expenditure. It has been demonstrated that a stepcounter is sensitive enough to discriminate activity levels related to job requirements and leisure-time PA levels (12,21). Thus, the Yamax may be a useful tool in large studies to rank individuals on PA but not to determine PAEE. The pedometer may be especially useful considering the low cost of this instrument compared with the accelerometers and DLW.

Maximum Aerobic Power

The measurement of maximum aerobic power is considered a measure of cardiovascular fitness. In the present study, DLW-PAEE was significantly correlated with $\dot{V}O_{2peak}$. $\dot{V}O_{2peak}$ explained 43% of the variance in DLW-PAEE. In African-American children, 48% of the variance in DLW-PAEE was explained by $\dot{V}O_{2peak}$ (unpublished results). Goran and Poehlman (9) reported that 71% of the variance in DLW-TDEE was explained by $\dot{V}O_{2max}$ in a group of elderly subjects. Starling et al. (28) reported that 18% of the variance DLW-PAEE was explained by $\dot{V}O_{2peak}$ in elderly Caucasian women and men. Although the present study had a small number of subjects, these results and those reported by Starling et al. (28) and Goran and Poehlman (9) may indicate that a subject with a high $\dot{V}O_{2peak}$ also has a high level of PA.

Phenotype research indicates that mitochondrial heritability for $\dot{V}O_{2peak}$ or changes in $\dot{V}O_{2peak}$ is about 30% in sedentary subjects. Maximal heritability for $\dot{V}O_{2peak}$ is estimated at 50% due to further contributions of nongenetic factors (2). The percent of variance in $\dot{V}O_{2peak}$ explained by PAEE of subjects in the current study may indicate an influence of PAEE on the nongenetic component of $\dot{V}O_{2peak}$. The results of this study may further confirm the suggestion that $\dot{V}O_{2peak}$ may also be a useful predictor for the level of PA, as well as physical fitness and cardiovascular health status (9,28).

In conclusion, PAR provided accurate groups estimates of PAEE compared with DLW. Individual assessments, however, were imprecise with overestimation of PAEE in the least active subjects and underestimation in the most active subjects. The Tritrac, and CSA accelerometer and Yamax stepcounter significantly underestimated DLW-PAEE. The Tritrac and CSA, however, can store data for a period of a couple of weeks and provide information about PA patterns, a feature not available with DLW. Thus, in studies where PA patterns are important the accelerometers may be useful to determine patterns of those movements, but they are unreliable as predictors of PAEE.

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REFERENCES

1. AINSWORTH, B. A., W. L. HASKELL, A. S. LEON, et al Compendium of physical activities: classification of energy cost of human physical activity. *Med. Sci. Sports Exerc.* 25:71–80, 1993.
2. BOUCHARD, C., E. W. DAW, T. RICE, et al. Familial resemblance for VO_{2max} in the sedentary state: the HERITAGE family study. *Med. Sci. Sports Exerc.* 30:252–258, 1998.
3. BOUTEN, C. V., K. R. WESTERTERP, M. VERDUIN, and J. D. JANSSEN. Assessment of energy expenditure for physical activity using a triaxial accelerometer. *Med. Sci. Sports Exerc*. 26:1616–1523, 1994.
4. BOUTEN, C. V., W. P. H. G. VERBOEKET-VAN DE VENNE, K. R. WESTERTERP, M. VERDUIN, and J. D. JANSSEN. Daily physical activity assessment: comparison between movement registration and doubly labeled water. *J. Appl. Physiol.* 81:1019–1026, 1996.
5. CHEN, K. Y., and M. SUN. Improving energy expenditure estimation by using a triaxial accelerometer. *J. Appl. Physiol.* 83:2112–2122, 1997.
6. ELIA, M. Energy equivalents of CO_2 and their importance assessing energy expenditure when using tracer techniques. *Am. J. Physiol.* 260:E75–E88, 1991.
7. FOGELHOLM, M., H.HILLOSKORPI, R. LAUKKANEN, P. OJA, W. VAN MARKEN LICHTENBELT, and K. WESTERTERP. Assessment of energy expenditure in overweight women. *Med. Sci. Sports Exerc.* 30: 1191–1197, 1998.
8. FREEDSON, P. S., E. MELANSON, and J. SIRARD. Calibration of the Computer Science and Applications Inc., accelerometer. *Med. Sci. Sports Exerc.* 30:777–781, 1998.
9. GORAN, M. I., and E. T. POEHLMAN. Total energy expenditure and energy requirements in healthy elderly persons. *Metabolism* 41: 744–753, 1992.
10. GORAN, M. I., W. I. CARPENTER, A. MCGLOIN, R. JOHNSON, M. HARDIN, and R. L. WEINSIER. Energy expenditure in children of lean and obese parents. *Am. J. Physiol.* 268:E917–E924, 1995.
11. GORAN, M. I., E. T. POEHLMAN, and R. K. JOHNSON. Energy requirements across the life span: new findings based on measurement of total energy expenditure with doubly labeled water. *Nutr. Res.* 15:115–150, 1995.
12. HATANO, Y. Use of the pedometer for promoting daily walking exercise. *ICHPER* 4–8:1993.
13. JAKICIC, J. M., C. WINTERS, K. LAGALLY, J. HO, R. J. ROBERTSON, and R. R. WING. The accuracy of the Tritrac-R3D accelerometer to estimate energy expenditure. *Med. Sci. Sports Exerc.* 31:747–754, 1999.
14. MONTOYE, H. J., H. C. G. KEMPER, W. H. M. SARIS, R. A. WASHBURN. *Measuring Physical Activity and Energy Expenditure*. Champaign, IL: Human Kinetics, 1996, pp. 17–25.
15. PHILIPPAERTS, R. M., K. R. WESTERTERP, and J. LEFEVRE. Doubly labelled water validation of three physical activity questionnaires. *Int. J. Sports Med.* 20:284–289, 1999.
16. POEHLMAN E. T., and E. S. HORTON. The impact of food intake and exercise on energy expenditure. *Nutr. Rev.* 47:129–136, 1989.
17. RACETTE, S. B., D. A. SCHOELLER, and R. F. KUSHNER. Comparison of heart rate and physical activity recall with doubly labeled water in obese women. *Med. Sci. Sports Exerc.* 27:126–133, 1995.
18. RAVUSSIN, E., S. LILLIOJA, T. E. ANDERSON, L. CHRISTIN, and C. BOGARDUS. Determinants of 24-hour energy expenditure in man: methods and results using a respiratory chamber. *J. Clin. Invest.* 78:1568–1578, 1986.
19. SALLIS, J. F. Seven-Day Physical Activity Recall. *Med. Sci. Sports Exerc.* 29:S89–S103, 1997.
20. SCHUTZ, Y., T. BESSARD, and E. JEQUIER. Diet-induced thermogenesis measured over a whole day in obese and non-obese women. *Am. J. Clin. Nutr.* 40:542–552, 1984.
21. SEQUEIRA, M. M., M. RICKENBACH, V. WIETLISBACH, B. TULLEN, and Y. SCHUTZ. Physical activity assessment using a pedometer and its comparison with a questionnaire in a large population survey. *Am. J. Epidemiol.* 142:989–999, 1995.
22. SERVAIS, S. B., J. G. WEBSTER, and H. J. MONTOYE. Estimating human energy expenditure using an accelerometer device. *J. Clin. Eng.* 9:159–170, 1984
23. SHERMAN, W. M., D. M. MORRIS, T. E. KIRBY, et al. Evaluation of a commercial accelerometer (Tritrac-R3D) to measure energy expenditure during ambulation. *Int. J. Sports Med.* 19:43–47, 1998.
24. SIMS, E. A. H., and E. DANFORTH, Jr. Expenditure and storage of energy in man. *J. Clin. Invest.* 79:1019–1025, 1987.
25. SIRI, W. E. Body composition from fluid spaces and density: analysis of methods. In: *Techniques for Measuring Body Composition*, J. Brozek and A. Hensen (Eds.). Washington, DC: National Academy Press, 1961, pp. 212–216.
26. SPEAKMAN, J. R., K. SPEEKUMARAN NAIR, and M. I. GORAN. Revised equations for calculating CO_2 production from doubly labeled water in humans. *Am. J. Pysiol.* 264:E912–E917, 1993.
27. STARLING, R. D., D. E. MATTHEWS, P. A. ADES, and E. T. POEHLMAN. Assessment of physical activity in older individuals: a doubly labeled water study. *J. Appl. Physiol.* 86:2090–2096, 1999.
28. STARLING, R. D., M. J. TOTH, W. H. CARPENTER, D. W. MATTHEWS, and E. T. POEHLMAN. Energy requirements and physical activity in free-living older women and men: a doubly labeled water study. *J. Appl. Physiol.* 85:1063–1069, 1998.
29. U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES. *Physical Activity and Health: A Report of the Surgeon General*. Atlanta, GA: U.S. Department of Health and Human Services, Centers of Disease Control and Prevention, National Center for Chronic Disease Prevention and Health Promotion, 1996, pp. 137.
30. WEIR, J. B DE V. New methods for calculating metabolic rate with special reference to protein metabolism. *J. Physiol.* 109: 1–9, 1949.