

Assessment of Low-to-Moderate Intensity Physical Activity Thermogenesis in Young Adults Using Synchronized Heart Rate and Accelerometry with Branched-Equation Modeling^{1,2}

Dylan Thompson,³ Alan M. Batterham, Susan Bock, Claire Robson, and Keith Stokes

Sport and Exercise Science Research Group School for Health, University of Bath, Bath BA2 7AY, UK

ABSTRACT Low-to-moderate intensity physical activity thermogenesis is a highly variable and quantitatively important component of total energy expenditure that is difficult to assess outside the laboratory. Greater precision and accuracy in the measurement of this key contributor to energy balance is a research priority. We developed a laboratory-based protocol that simulated a range of low-to-moderate intensity physical activities. We characterized the bias and random (individual) error in estimating energy expenditure using combined accelerometry and heart rate (AHR) with branched-equation modeling and a simple motion sensor (pedometer) against an indirect calorimetry criterion. Twenty young adult subjects performed a 2-h laboratory-based protocol, simulating 6 low-to-moderate intensity physical activities interspersed with periods of rest. The physical activity level during the laboratory-based protocol reflected an energy expenditure toward the lower end of the active category. We found that AHR-derived energy expenditure showed no evidence of substantial fixed or proportional bias (mean bias 6%), whereas pedometer-derived energy expenditure showed both fixed and proportional bias (bias at minimum, mean, and maximum energy expenditure +11, -20, and -36%, respectively). It appears that AHR provides an accurate estimate of criterion energy expenditure whereas a simple motion sensor (pedometer) does not. It is noteworthy that AHR provides quantitative information about the nature and patterns of physical activity, such as the amount of time and/or energy spent engaged in physical activity above critical health-related thresholds. *J. Nutr.* 136: 1037–1042, 2006.

KEY WORDS: • *energy expenditure* • *physical activity* • *nonexercise activity thermogenesis*
• *spontaneous physical activity*

The assessment of physical activity thermogenesis away from the laboratory remains extremely problematic. Physical activity can occur in multiple contexts for different purposes, including transportation, occupation, household maintenance, child-care tasks, and recreation (1,2). In terms of energy expenditure, low-to-moderate intensity physical activity is likely to be quantitatively the most important for any given individual or population (2–4). Unfortunately, it is our ability to assess low-to-moderate physical activity that is especially limited because these activities tend to be poorly recalled and are either routine or spontaneous in nature (1,2,5).

At present, there is no single technique that will satisfactorily determine activity energy expenditure and at the same time provide information on the nature of the physical activity (i.e., provide information on intensity, duration, frequency, and timing of physical activity). The doubly labeled water method is extremely good for estimating the mean total carbon dioxide

production (and therefore total energy expenditure) of a defined group or population over a period of days or weeks (bias of 1–7%, depending on the specific pool size and pool ratio model adopted) (6–9). Using estimated or measured resting metabolic rates, activity energy expenditure can then be estimated by deduction (with or without correction for the thermic effect of feeding). However, the doubly labeled water technique is expensive and, moreover, does not provide specific information on the nature of physical activity energy expenditure (e.g., the frequency, intensity, or duration of physical activity). Indeed, it is not possible to determine whether an individual or population is meeting current physical activity recommendations using doubly labeled water (e.g., undertaking 30 min of moderate intensity physical activity most days of the week either in a continuous period or in blocks of 10 min or greater). At the opposite end of the spectrum, questionnaires represent low-cost options that would, ostensibly, provide information on these aspects of physical activity. However, the reliability and validity of all self-report methods is limited by issues such as subject compliance, misreporting, miscoding of activities, inaccurate estimation of activity intensity or duration, differences in body mass, and the environment (5,10,11). Clearly, improved methodologies for assessing low-to-moderate intensity physical activity energy expenditure in the field are required.

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³ To whom correspondence should be addressed. Email: d.thompson@bath.ac.uk.

A potential solution to these problems has been the development of motion sensors for the assessment of physical activity (12,13). Although these instruments are useful, it is unfortunate that motion sensors fail to detect certain forms of physical activity. For example, accelerometers underestimate the cost of activities, such as golf and household tasks, by as much as 55% (12) and completely overlook other forms of activity (e.g., cycling). A potential solution to these problems is the simultaneous use of a motion sensor with a heart rate monitor and, although this has been attempted in the past (14–16), it is only recently that a combined single-piece device has been developed for this purpose (17). This instrument uses a novel branched-equation model to improve estimates of energy expenditure above rest (18) and has been validated in ambulatory activities such as walking and running (17). However, during walking and running, estimates of energy expenditure through a simple motion sensor (e.g., pedometer) would probably suffice, and it is therefore more important to understand the ability of this approach to determine energy expenditure during a variety of low-to-moderate-intensity activities. Therefore, the aims of the present study were to 1) develop a representative laboratory-based protocol that simulated low-to-moderate intensity physical activities and 2) characterize the bias and random (individual) error in estimating energy expenditure, using a combined heart rate and motion sensor with branched-equation modeling.

MATERIALS AND METHODS

Subjects. Twenty subjects volunteered to take part in this investigation (10 male and 10 female) following approval from the Bath NHS Research Ethics Committee. The subjects' age, height, and body mass were (mean \pm SD) 25 ± 5 y, 173 ± 7 cm, and 71.7 ± 11.3 kg, respectively. All subjects were informed verbally and in writing about the nature and demands of the study, subsequently completed a physical activity readiness questionnaire, and gave their written informed consent. Volunteers were excluded if they gave a positive response to any questions on the questionnaire or if they reported being a smoker.

Low-to-moderate intensity physical activity protocol. A laboratory-based protocol was developed to reflect low-to-moderate intensity physical activities. Activities were selected based upon classification of estimated energy expenditure using the Compendium of Physical Activities expressed in metabolic equivalents tasks (METs)⁴ defined as multiples of typical resting oxygen uptake ($3.5 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ in adults) (19). In order to capture information on a range of low-to-moderate intensity activities, the following tasks were selected: level walking at $4.8 \text{ km} \cdot \text{h}^{-1}$ (3.3 METs, Code 17190), sweeping with a broom (4.0 METs, Code 05140), digging and transferring in sand boxes (5.0 METs, Code 08040), simulated watering of house plants with a watering can (2.5 METs, Code 05148), level walking at $5.6 \text{ km} \cdot \text{h}^{-1}$ carrying 8% of body mass (4.5 METs, Code 11810), and folding and stacking laundry (2.0 METs, Code 05090). Importantly, these activities were chosen to involve a variety of different movements, including those where the assessment of the demands of activity is particularly problematic outside the laboratory. Subjects were instructed to continuously perform each activity for 8 min. This allowed time for the demands of each activity to reach steady state before being assessed between 3 and 7 min of each 8-min block. Prior to the first activity, and following each activity, subjects sat and rested quietly for 8 min. All subjects were required to arrive in the laboratory in the morning after a fast of at least 12 h.

Walking activities took place on a treadmill (Woodway ELG 70). During the sweeping activity, the subjects brushed polystyrene chippings back and forth along a hard surface (~ 6 m). During the digging activity, subjects were asked to continuously dig and transfer

sand between 2 plastic boxes placed adjacent to each other. The simulated watering of house plants activity required subjects to half fill a plastic watering can from a sink located ~ 10 m from a series of 6 vessels placed at different heights (range 0–80 cm) in a rectangular space ($\sim 12 \text{ m}^2$). During walking and carrying, the load was distributed in 2 shopping bags (4% body mass in each hand). The folding and stacking activity required subjects to continuously untangle cotton sheets placed on a flat surface ~ 50 cm from the floor and neatly fold and stack each item. These were continuously recycled by the experimenters to ensure that sheets were always available.

Assessment of relative activity intensity and energy expenditure. Oxygen uptake and carbon dioxide production was measured during each activity and rest period, using a portable gas analysis system calibrated immediately prior to use according to the manufacturer's instructions (Cosmed K4b²). Using these data, the relative exercise intensity was determined using measured oxygen uptake during each activity and expressed in METs. Furthermore, measured oxygen uptake and carbon dioxide production were used to estimate energy expenditure (kJ/min) during each activity, using indirect calorimetry (20). In addition, predicted activity intensity from the compendium of physical activities in METs (19) was used to estimate energy expenditure, using the predicted total amount of oxygen consumed, where 1 liter of oxygen consumed = 20 kJ of energy expended (21).

Subjects also wore a combined accelerometer and heart rate monitor (AHR) (Actiheart, Cambridge Neurotechnology) that has been described in detail previously (17). Each unit was fitted using ECG electrodes according to manufacturer's instructions (MACS, Unomedical). Accelerometer counts and heart rate were used to estimate energy expenditure using equations and software provided by the manufacturer:

$$\begin{aligned} \text{Physical Activity Intensity (PAI, } \text{J} \cdot \text{min}^{-1} \cdot \text{kg}^{-1}) \\ = 5.95 \times \text{HraS} - 134 + 0.23 \times \text{age(y)} + 84 \\ \times \text{sex (coded 0 for females and 1 for males).} \end{aligned} \quad (1)$$

$$\begin{aligned} \text{Physical Activity Intensity (PAI, } \text{J} \cdot \text{min}^{-1} \cdot \text{kg}^{-1}) \\ = 0.203 \times \text{counts}/\text{min} + 46 - 0.75 \times \text{age(y)} + 83 \\ \times \text{sex (coded 0 for females and 1 for males).} \end{aligned} \quad (2)$$

HraS represents heart rate above sleep, and counts/min represents accelerometer counts/min.

These equations are used in conjunction with a branched modeling technique described previously (18). Predicted basal metabolic rate was added to activity energy expenditure to derive total energy expenditure (22).

In order to place the AHR results in context, each activity was also assessed with a pedometer positioned above the right hip (Yamax DW 351). Using body mass combined with age and sex-specific reference data for typical step length (23), we estimated energy expenditure using predicted oxygen uptake for predicted distance traveled according to established and validated equations (24).

Twenty-four-hour record. Subjects were asked to carry out their normal daily activities during a typical working day for a period of 24 h while being monitored using AHR to establish sleeping heart rate (defined as the 10th lowest observation during the night (17)). This short observation also provided a 24-h snapshot of physical activity in these subjects. In addition, subjects were asked to log their physical activity as accurately as possible to estimate energy expenditure using the compendium of physical activities (19), and they were also fitted with the same pedometer described above.

Twenty-four-hour energy expenditure was estimated from self-reported physical activity, the pedometer, and AHR. In addition, total time spent in moderate intensity activity or higher (>3 METs), time spent in moderate intensity or higher for periods longer than 10 min ($\text{Time}^{10} > 3$ METs), and estimated peak energy expenditure were calculated from the physical activity record and AHR. One subject failed to satisfactorily record physical activity using the compendium (the record terminated approximately half way through the 24-h period), and a pedometer failed with an additional subject; therefore, these data are only available for 18 subjects.

⁴ Abbreviations used: AHR, accelerometry and heart rate; MET, metabolic equivalent; PAI, physical activity intensity; PAL, physical activity level.

Method comparisons. The criterion measure for the method comparison was energy expenditure predicted from indirect calorimetry. The mean energy expenditure for the 104-min block of simulated low-to-moderate-intensity activities (recalculated to kJ/min) was the variable of interest. Preliminary inspection of plots of between-method differences vs. the mean of the 2 methods (not shown) revealed complex relations between difference and mean, precluding a standard Bland-Altman limits of agreement analysis. These problems could not be resolved adequately through the transformation or regression modeling approaches suggested by Bland and Altman (25). For the present study, a more robust analysis of the bias of AHR- and pedometer-estimated energy expenditure against indirect calorimetry is provided by the nonparametric Passing-Bablok technique (26,27). All analyses were conducted using the Analyze-it™ clinical laboratory software. For each comparison, the predictor method was regressed on the criterion [e.g., AHR energy expenditure = $a + b \times \text{IC}$; where IC is the energy expenditure (kJ/min) from the indirect calorimetry criterion and AHR energy expenditure is the predicted energy expenditure from the AHR method]. The analyses were conducted on the sample as a whole, as diagnostic checks revealed no substantial influence of sex on the regression slopes. Unlike ordinary least-squares regression, the Passing-Bablok method allows for imprecision in both the reference method (indirect calorimetry) and the comparison method (AHR or pedometer). Importantly, with respect to the current study, this imprecision need not be normally distributed, it can have nonconstant variance over the sampling range, and the Passing-Bablok regression line is not biased strongly by outliers. Fixed bias was indicated if the 95% confidence interval (CI) for the intercept (a) did not include zero. Proportional bias was revealed if the slope (b) (95% CI) differed from unity. Overall bias of each method compared with the criterion was calculated from the Passing-Bablok regression equation at 3 important criterion energy expenditure values (the mean, the minimum, and the maximum) for the 20 subjects in the current study. This bias was calculated as $\hat{Y} - X$, where \hat{Y} is the energy expenditure predicted from the regression equation at a given criterion energy expenditure (X ; the mean, minimum, or maximum).

The above calculations provide the mean systematic error (bias) for the sample. Total error for the predictor methods against the criterion is composed of systematic error plus random error (likely range for the differences between methods for individual subjects). Random error for each method was estimated using a nonparametric resampling technique (Resampling Stats). Repeat samples of 20 cases, with replacement, were drawn from the original sample of 20 subjects. For each of 5000 resamples, the 20 individual between-method differences (indirect calorimetry-predicted energy expenditure minus predictor method) were calculated. The value representing the range for the 16th to 84th percentile of the distribution of these differences was stored after each run. These 5000 values were then plotted and the median of this distribution recorded. This technique provides a nonparametric analog of the standard deviation of the differences,

representing the range within which the true random between-method measurement error would lie for the majority (approximately two-thirds) of individuals. The total error for a predictor method compared with the criterion is therefore the bias \pm the random error. This total error is analogous to the mean difference \pm SD of the differences in a Bland-Altman limits of agreement analysis. All summary statistics are reported as mean \pm SD.

RESULTS

Low-to-moderate intensity physical activity protocol. The energy cost of the protocol determined using indirect calorimetry ranged from low to moderate intensity physical activity (Table 1 and Fig. 1). Activity intensity determined by indirect calorimetry was generally lower than that estimated from the compendium of physical activities, particularly for activities where intensity was self-regulated by each subject, such as digging (Table 1 and Fig. 1).

If this level of activity was maintained for an estimated 16-h waking day, this would equate to energy expenditure of 8928 kJ (2134 kcal, where 1 kcal = 4.184 kJ) during this period (9.3 kJ/min \times 960 min). If, for the purpose of illustration only, we assume that resting energy expenditure was maintained for an additional 8 h (4.6 kJ/min \times 480 min), this would equate to a total energy expenditure of 11136 kJ (2662 kcal) in 24 h (8928 + 2208 kJ).

Estimated energy expenditure: AHR and pedometer.

Passing-Bablok regression for mean energy expenditure during the low-to-moderate intensity protocol was used to examine bias between estimated and criterion energy expenditure (Fig. 2). To place these values into context, energy expenditure was extrapolated to a hypothetical 16-h waking day (i.e., energy expenditure in kJ/min \times 960 min). Estimated energy expenditure from AHR, extrapolated over a hypothetical 16 h waking day, showed a bias at the mean energy expenditure of -521 kJ or -6% (i.e., $-521 \div 8928 \times 100$) (Fig. 2). The bias at the minimum and maximum energy expenditure observed for our sample is equivalent to -1 and -8% of energy expended for the minimum and maximum. There was no evidence of substantial fixed or proportional bias for AHR (Table 2).

Estimated energy expenditure from the pedometer, extrapolated over a hypothetical 16-h waking day, showed a bias at the mean energy expenditure of -1817 kJ (434 kcal) or -20%

TABLE 1

Human energy expenditure and intensity during the laboratory-based protocol¹

	Compendium		Indirect calorimetry		AHR		Pedometer	
	METs	kJ/min	METs	kJ/min	METs	kJ/min	Steps	kJ/min
Walking	3.3	16.6 \pm 2.6	3.1 \pm 0.6	15.7 \pm 4.4	2.9 \pm 0.5	14.9 \pm 4.5	872 \pm 33	17.3 \pm 3.0
Sweeping	4.0	20.1 \pm 3.2	2.8 \pm 0.9	14.4 \pm 5.9	2.3 \pm 0.6	11.7 \pm 4.5	128 \pm 96	6.8 \pm 1.4
Digging in sand	5.0	25.1 \pm 3.9	3.3 \pm 0.7	16.8 \pm 5.4	2.3 \pm 0.7	12.3 \pm 4.4	25 \pm 26	5.4 \pm 0.8
Watering plants	2.5	12.5 \pm 2.0	1.9 \pm 0.5	9.6 \pm 3.3	1.7 \pm 0.4	8.5 \pm 2.8	185 \pm 34	7.6 \pm 1.2
Walking and carrying	4.5	22.6 \pm 3.6	4.3 \pm 0.6	21.7 \pm 5.8	3.6 \pm 0.5	18.6 \pm 5.1	944 \pm 37	18.3 \pm 3.2
Folding and stacking	2.0	10.0 \pm 1.6	2.1 \pm 0.5	10.8 \pm 4.0	1.8 \pm 0.5	9.3 \pm 3.6	34 \pm 24	5.5 \pm 1.0
Rest (mean of 7) ²	1.0 \pm 0.0	5.0 \pm 0.8	0.9 \pm 0.2	4.6 \pm 1.3	1.0 \pm 0.1	5.2 \pm 0.9	—	5.0 \pm 0.8
Mean (exercise only) ³	3.6 \pm 0.0	17.8 \pm 2.8	2.9 \pm 0.6	14.8 \pm 4.8	2.4 \pm 0.5	12.4 \pm 4.3	365 \pm 42	10.2 \pm 1.8
Mean (full protocol) ⁴	2.2 \pm 0.0	10.9 \pm 1.7	1.8 \pm 0.4	9.3 \pm 2.7	1.7 \pm 0.3	8.6 \pm 2.4	—	7.4 \pm 1.2

¹ Values are means \pm SD, $n = 20$.

² The values for rest are the means of all 7 rest periods throughout the protocol.

³ The values for exercise only do not include rest periods.

⁴ The values for full protocol include all activities and all rest periods (104 min).

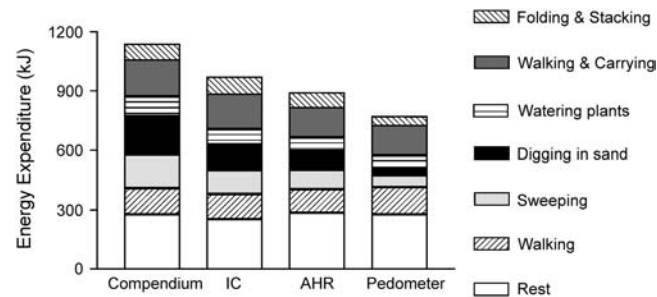


FIGURE 1 Estimated total energy expenditure during the 104-min laboratory-based protocol. In addition, the proportion of energy expended during each activity and the sum of all 8-min rest periods is also shown ($n = 20$). Values represent mean energy expenditure by young adults for the group multiplied by the total time of each activity.

(i.e., $-1817 \div 8928 \times 100$) (Fig. 2). The bias at the minimum and maximum for the pedometer was equivalent to 11 and -36% of energy expended, respectively. Pedometer-estimated energy expenditure showed evidence of both fixed and proportional bias (Table 2).

The random error for AHR was 1326 kJ (317 kcal) (using data extrapolated over 16 h) and for the pedometer it was 1527 kJ (365 kcal). Criterion estimated energy expenditure over this period was 8928 kJ (2134 kcal), and therefore the random error expressed as a percentage of the criterion represents 15 and 17% for AHR and the pedometer, respectively. The total error (i.e., mean bias \pm random error) for AHR ranges from an overestimation of 804 kJ (192 kcal) (i.e., $-521 + 1326$ kJ) to an underestimation of 1847 kJ (441 kcal) (i.e., $-521 - 1326$ kJ). The total error for the pedometer at the mean energy expenditure ranges from an underestimation of 290 kJ (69 kcal) (i.e., $-1817 + 1527$ kJ) to an underestimation of 3344 kJ (799 kcal) (i.e., $-1817 - 1527$ kJ). However, due to the substantial proportional bias exhibited by the pedometer, the total error at the maximum energy expenditure ranges from an underesti-

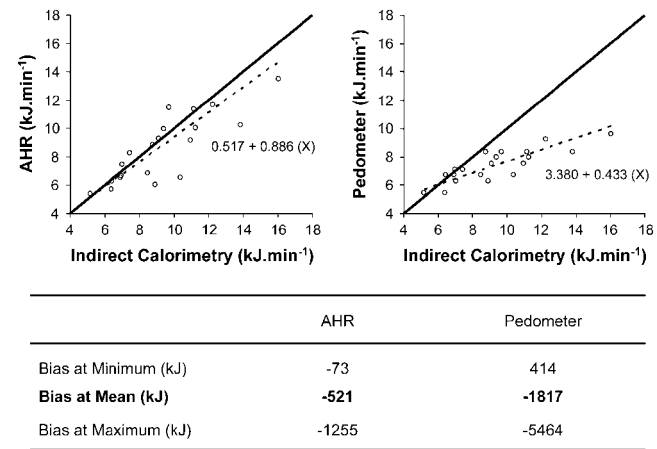


FIGURE 2 Passing-Bablok regression derived from mean energy expenditure by young adults during the laboratory-based protocol using indirect calorimetry, AHR, and pedometers. Each regression was based on $n = 20$. For the sake of comparison, the line of identity is also included (bold line). Estimated systematic bias against the indirect calorimetry criterion is presented using mean energy expenditure (kJ/min) extrapolated to a hypothetical 16-h wake cycle. Bias calculations are obtained from the Passing-Bablok method conversion regression line of the form $Y = a + bX$, where Y is the alternative method and X is the criterion (kJ/min). Bias is presented for representative criterion energy expenditures of the mean, minimum, and maximum values observed for the sample.

TABLE 2

Checks for fixed bias and proportional bias against the indirect calorimetry criterion in young adults¹

	95% CI for intercept ²	Fixed bias?	95% CI for slope ²	Proportional bias?
AHR	-0.55 to 0.59	No	0.64 to 1.26	No
Pedometer	0.47 to 1.14	Yes	0.29 to 0.60	Yes

¹ Values are the 95% CI for fixed bias (intercept $\neq 0$) and proportional bias (slope $\neq 1$) for each method against the indirect calorimetry criterion.

² CI are derived from the Passing-Bablok regressions (method-comparison algorithm) shown in Fig. 2.

mation of 3937 kJ (941 kcal) (i.e., $-5464 + 1527$ kJ) to an underestimation of 6991 kJ (1671 kcal) (i.e., $-5464 - 1527$ kJ).

Twenty-four-hour record. Mean total energy expenditure and PAL estimated using AHR away from the laboratory were very similar to those derived from the compendium of physical activities whereas pedometer-derived values were markedly different (Table 3).

DISCUSSION

Our understanding of the role of low-to-moderate intensity physical activity thermogenesis in energy balance and health has been hampered by the inability to adequately assess physical activity energy expenditure away from the laboratory. We developed a laboratory-based protocol to allow us to characterize the bias and random (individual) error in estimating low-to-moderate intensity physical activity energy expenditure using a combined heart rate and motion sensor that employs a novel branched-equation model based on accelerometer counts and heart rate above sleep (AHR).

Low-to-moderate intensity physical activity is likely to be the most variable component of activity thermogenesis in most people (2–4). The first research priority was therefore to validate AHR against the criterion measure of energy expenditure

TABLE 3

Energy expenditure and time engaged in moderate intensity physical activity over 24 h in young adults¹

	Compendium	AHR	Pedometer
Total EE, ² MJ	13.4 \pm 3.4	13.4 \pm 3.9	9.2 \pm 1.6
PAL	1.83 \pm 0.35	1.84 \pm 0.38	1.27 \pm 0.12
Mean EE, ³ kJ/min	11.3 \pm 3.8	11.3 \pm 4.8	7.1 \pm 1.3
Peak EE, kJ/min	43.5 \pm 27.2	56.9 \pm 20.5	—
Time > 3 METs, ⁴ min	151 \pm 93	130 \pm 76	—
Time ¹⁰ > 3 METs, ⁵ min	134 \pm 93	83 \pm 63	—
Pedometer counts	—	—	17147 \pm 4926

¹ Values are means \pm SD, $n = 18$. One subject failed to satisfactorily record physical activity and a pedometer failed with an additional subject; therefore these data are available only for 18 subjects.

² EE, total energy expenditure, is the sum of activity energy expenditure and estimated basal metabolic rate over 24 h.

³ Mean energy expenditure is calculated based on a wake:sleep cycle of 16:8 h over the period of observation (i.e., total energy expenditure, estimated energy expenditure during 8-h sleep, 960 min).

⁴ Time >3 METs is the total time engaged in physical activity >3 METs.

⁵ Time¹⁰ >3 METs is the total time engaged in physical activity >3 METs, where activity was accumulated in blocks of at least 10 min.

during physical activity (i.e., indirect calorimetry) to understand the potential utility of this approach in the field. Within this context, our newly developed laboratory-based protocol was representative of typical physical activity energy expenditure outside the laboratory. The activities were low-to-moderate intensity in nature as determined by indirect calorimetry (1.9 to 4.3 METs) and, importantly, the protocol included nonambulatory physical activities that have been historically very difficult to assess away from the laboratory (e.g., folding and stacking sheets). Activities with a significant walking component were responsible for just over half of energy expended through activity. Extrapolated over a hypothetical 24-h d (with a theoretical wake:sleep cycle of 16:8 h), this would equate to a daily energy expenditure of 11.1 MJ (2662 kcal). Using measured resting metabolic rate, this would equate to an estimated physical activity level (PAL) of 1.68 over 24 h, which is described as being toward the bottom of the active category (28). Therefore, the laboratory-based protocol is ideally suited for assessing the ability of AHR to estimate activity energy expenditure during representative physical activity.

Energy expenditure estimated by AHR was evaluated against the criterion measure of indirect calorimetry. For comparison, a simple low-cost and widely used motion sensor (pedometer) was also included. Estimated energy expenditure from AHR showed no fixed or proportional bias with the estimated bias at the mean energy expenditure for our sample, indicating a modest 6% underestimate of energy expenditure. It remains unclear whether the technique (especially the use of the default manufacturer's equations) is equally useful in older and younger populations or populations that differ markedly in some other way (e.g., body composition). In contrast to AHR, the pedometer showed both fixed and proportional bias with estimated bias at the mean for our sample, representing a 20% underestimate of the true value determined by indirect calorimetry. In particular, the pedometer failed to characterize the difference between high and low energy expenditure values during the protocol, with the underestimation increasing progressively up to the maximum values observed for the laboratory-based protocol. This indicates that additional energy was being expended that was not ambulatory in nature and therefore overlooked by the pedometer as reported previously (29). The random (individual) error estimates were similar for the AHR and pedometer. However, the mean bias for the pedometer, coupled with the random error, indicates that for an individual it could substantially underestimate energy expenditure over a 16-h waking cycle. The limitation of the pedometer is exacerbated by the substantial proportional bias, which leads to even greater discrepancies from the criterion measure at the upper end of the energy expenditure range. In comparison, the AHR displays much better accuracy and precision. Therefore, for the group of lean young men and women in the present study, AHR provides a reasonable estimate of energy expenditure during representative low-to-moderate intensity physical activities, whereas a pedometer does not.

It is important to consider our findings in the context of alternative techniques that can be used in the field. Doubly labeled water can provide excellent estimates of total energy expenditure (6,8,9) and therefore estimate physical activity energy expenditure by difference (i.e., physical activity thermogenesis = total energy expenditure – estimated or measured resting metabolic rate and diet-induced thermogenesis). Using AHR, it is now possible to directly determine physical activity thermogenesis away from the laboratory, and this technique therefore serves to complement existing field-based approaches such as doubly labeled water. In this context, and to make preliminary observations about the utility of AHR in the field,

the same subjects completed a short 24-h record of physical activity using AHR, the compendium of physical activities (19), and a pedometer. Estimated energy expenditure from AHR and the compendium of physical activities were remarkably similar in terms of total energy expenditure over this period and estimated PAL categorizes these subjects as highly active over this short period of observation (28). Importantly, AHR offers the opportunity to determine physical activity energy expenditure and to use this information to objectively characterize the nature of physical activity according to predetermined criteria (e.g., time and/or energy spent engaged in physical activity >3 METs in bouts of at least 10 min). This additional characteristic is important because physical activity is associated with benefits that go well beyond its effects on energy turnover and energy balance (1,28), and this aspect of physical activity has been traditionally very difficult to assess (1).

Pedometer-estimated energy expenditure over 24 h was markedly different from that estimated by AHR and the compendium of physical activities. Indeed, the estimated total energy expenditure over this period would translate to a PAL of 1.27 and classify these subjects as sedentary (28). This supports our laboratory-based observation that a simple pedometer underestimates true energy expenditure. Interestingly, this sedentary classification is despite the fact that subjects undertook over 7000 steps more than the 10,000-step recommendation (30). This emphasizes the point that the 10,000 steps/d recommendation recognizes that the largest proportion of activity energy that is expended is not ambulatory and is therefore inevitably overlooked by a simple motion sensor. These observations do not detract from the utility of pedometers to assess ambulatory physical activity or to serve potentially as a motivational tool in walking or running interventions. However, our findings do reinforce the fact that pedometer counts should not be used as a surrogate measure of physical activity because pedometers fail to capture many of the activities that have the potential to make a large contribution to activity energy expenditure (31). Furthermore, in contrast to AHR, pedometers do not capture data regarding patterns of physical activity, such as the amount of energy or time engaged in physical activity above critical intensity thresholds.

In conclusion, we successfully developed a laboratory-based protocol that is representative of typical activity thermogenesis. Utilizing this protocol, it appears that AHR provides a reasonable estimate of criterion energy expenditure, whereas a simple motion sensor (pedometer) showed evidence of large systematic bias. Importantly, AHR provides additional information about the nature and patterns of physical activity, such as the amount of time and/or energy spent engaged in physical activity above critical thresholds. This technique has the potential to directly characterize and quantify low-to-moderate intensity physical activity thermogenesis, one of the most labile and variable components of energy expenditure in humans (2–4).

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