Validity of the simultaneous heart rate-motion sensor technique for measuring energy expenditure

SCOTT J. STRATH, DAVID R. BASSETT, JR., DIXIE L. THOMPSON, and ANN M. SWARTZ

Department of Exercise Science and Sport Management, The University of Tennessee, Knoxville, TN 37996-2700

ABSTRACT

STRATH, S. J, D. R. BASSETT, Jr., D. L. THOMPSON, and ANN M. SWARTZ. Validity of the simultaneous heart rate-motion sensor technique for measuring energy expenditure. *Med. Sci. Sports Exerc.*, Vol. 34, No. 5, pp. 888–894, 2002. **Purpose:** To determine the validity of the simultaneous heart rate-motion sensor (HR+M) technique for estimating energy expenditure (EE) by comparing it with indirect calorimetry. In addition, we examined the validity of the flex heart rate (FlexHR) method to estimate EE. **Methods:** Ten participants (4 men: 26.7 yr ± 1.5, and 6 women: 26.5 yr ±3.3) performed arm and leg work in the laboratory for the purpose of developing individualized HR-oxygen uptake ($\dot{V}O_2$) regression equations. Participants completed physical tasks in a field setting while HR, $\dot{V}O_2$, and motion sensor data were collected on a near-continuous basis for 6 h. Accelerometers, one on the arm and one on the leg, were used to discriminate between upper- and lower-body movement. HR was used to predict EE (METs) from the corresponding laboratory regression equation. Predicted values (METs) were compared with measured values (METs) obtained via a portable metabolic measurement system. **Results:** The simultaneous HR+M technique showed a significantly stronger relationship with $\dot{V}O_2$ (R^2 = 0.81, SEE = 0.55 METs) in comparison with the FlexHR method (R^2 = 0.63, SEE = 0.76 METs) ($P < 0.001$). The FlexHR method significantly overestimated measured minute-by-minute EE ($P < 0.001$), whereas the simultaneous HR+M technique did not. The simultaneous HR+M technique accurately reflected time spent in resting/light, moderate, and hard activity, whereas the FlexHR method underpredicted time spent in resting/light activity ($P = 0.02$) and overpredicted time spent in moderate activity ($P = 0.02$). The simultaneous HR+M technique also accurately estimated total 6-h EE. **Conclusion:** The simultaneous HR+M technique is an accurate predictor of EE during free-living activity and provides a valid measure of the time spent in various intensity categories. **Key Words:** PHYSICAL ACTIVITY, OXYGEN UPTAKE, ACCELEROMETER, VALIDITY.

Evidence has accumulated over the years supporting the role of physical activity (PA) in preventing or managing certain chronic diseases (5,8,14,16–18,20,21). Based on this research, many health organizations conclude that there is a causal association between PA and health (1,2,4,24). Even with a plethora of scientific evidence supporting the association between PA and health, there still remains a great deal to be learned about the type, intensity, frequency, and duration of PA needed to elicit specific health benefits and prevent certain diseases.

To better define the dose-response relationship between PA and health, it is necessary to accurately quantify physical activity energy expenditure (PAEE). Haskell et al. (7) proposed that the simultaneous use of heart rate (HR) and motion sensors may increase the accuracy of energy expenditure (EE) prediction over either method used independently. It was suggested that individual calibration curves between HR and oxygen uptake ($\dot{V}O_2$) first be established in the laboratory for both arm and leg exercise, then, in the field setting, motion sensors could discriminate between arm and leg movement, and HR could be used to predict $\dot{V}O_2$ from the corresponding regression equation. Recently, our laboratory demonstrated that this technique can more accurately quantify EE than either motion sensors or HR used individually during selected 15-min lifestyle tasks (22).

In 1996, the U.S. Surgeon General's Report recommended the accumulation of 30 min or more of moderate intensity PA on most, if not all, days of the week (24). This emphasized the need for a method of PA assessment to accurately detect time spent in different intensity categories. Thus, the purpose of this study was to test the validity of the simultaneous HR+M technique over 6 h of near-continuous measurement to estimate EE and predict time spent in various PA intensity categories. A secondary purpose was to examine the validity of the flex heart rate (FlexHR) method to estimate the same variables aforementioned.

MATERIALS AND METHODS

Ten participants (4 men and 6 women) from the Knoxville, TN, area volunteered to take part in this study. Four subjects were graduate students, three were undergraduate students, and the remaining three had white-collar clerical occupations. Participants with clerical occupations were monitored on workdays, whereas the students were monitored on either workdays or nonworkdays (see Table 1). Each participant read and signed an informed consent form approved by the University of Tennessee's Institutional

0195-9131/02/3405-0888/$3.00/0
MEDICINE & SCIENCE IN SPORTS & EXERCISE®

Submitted for publication April 2001.
Accepted for publication September 2001.

TABLE 1. Descriptive characteristics of the study participants.

Subject	Gender	Age (yr)	Height (m)	Mass (kg)	BMI ($kg \cdot m^{-2}$)	Day of Observation
1	F	27	1.67	62.1	22.3	M
2	M	28	1.80	77.0	23.8	Sa
3	M	25	1.88	75.2	21.3	F
4	F	22	1.57	91.0	36.9	R
5	F	25	1.63	59.1	22.2	F
6	M	29	1.80	72.4	22.3	T
7	F	31	1.71	57.3	19.6	W
8	F	28	1.57	71.8	29.1	Su
9	M	20	1.92	88.6	24.0	R
10	F	23	1.65	62.1	22.8	W
Mean		25.8	1.70	71.7	24.4	
SD		3.4	0.1	11.8	5.0	

Review Board before participation. A health history questionnaire was also completed by all participants to screen for any contraindications to exercise.

Before testing, participants had their body mass measured to the nearest 0.1 kg using a calibrated physician's scale (Health-O-Meter, Bridgeview, IL), and their height measured to the nearest 0.1 cm using a stadiometer (Seca Corp., Columbia, MD). Descriptive characteristics of the participants are listed in Table 1.

Procedures

Participants were asked to come to the Applied Physiology Laboratory having abstained from exercise for at least 12 h and in a postprandial state for at least 2 h. After completing the health history questionnaire and informed consent, anthropometric measurements were performed. Afterward, each person was fitted with a Polar HR watch (Polar NV, Polar Oy, Kempele, Finland), a transmitter band placed around the chest, and a portable metabolic measurement system (Cosmed K4b^2, Cosmed, S.r.L, Rome, Italy [see Equipment section]). Participants were then instructed to remain in a supine position for a 10-min period. They then sat upright for 5 min and stood for an additional 5 min. After these rest periods, each participant completed a submaximal leg exercise test, followed by a submaximal arm ergometer exercise test. Between each submaximal exercise test, participants were in a supine position for 30–45 min. This rest period was included to attain resting physiological levels (HR and $\dot{V}O_2$ within 5% of initial rest values) before the second test began. HR and $\dot{V}O_2$ were continuously measured throughout all rest and exercise periods.

After the completion of both submaximal exercise tests, individualized arm and leg regression equations for HR and $\dot{V}O_2$ were developed. Data from the individualized regression analyses for each activity were combined to demonstrate the different relationship between HR and $\dot{V}O_2$ for arm and leg exercise (Fig. 1). Participants did not perform combined arm-and-leg activity as this has been shown to closely reflect the legs-only condition (7). Figure 1 demonstrates the different relationship between arm and leg work by using group regression data, although individualized regressions were used for predicting EE. This was done to provide greater accuracy, as other investigators have shown that utilizing group regression equations introduces greater error than when using individualized regression equations (7,13).

Experimental Protocols

Submaximal treadmill test. Participants walked on a treadmill (Quinton Instrument Co., Q65, Bothell, WA) following an incremental protocol, consisting of continuous 3-min stages. Initial speed was 2.5 mph and was increased to 3.5 mph, after which speed remained constant while grade was increased 2% each stage. The test was terminated once the participant reached 80–85% of age-predicted maximal HR. During this time, HR was measured using a Polar HR Vantage NV watch and transmitter, and $\dot{V}O_2$ was measured using the Cosmed K4b^2.

Submaximal arm ergometer test. Participants performed successive 3-min stages on an arm ergometer (Monark 881E, Varberg, Sweden). The initial cadence was set at 50 rpm and initial resistance at 0 kp. Thereafter, cadence remained constant and resistance increased by 0.25 kp each stage. The test was terminated once the participant reached 80–85% of age-predicted maximal HR. Heart rate and $\dot{V}O_2$ were again measured by a Polar HR Vantage NV watch and transmitter, and Cosmed K4b^2, respectively.

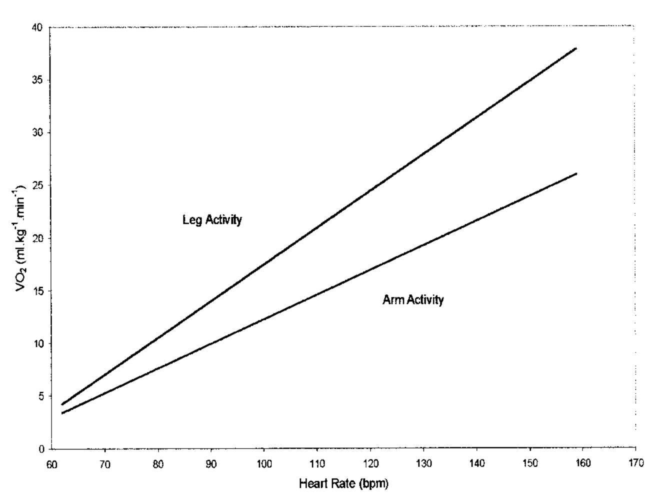

FIGURE 1—The relationship between heart rate and measured oxygen uptake during treadmill walking and arm ergometer exercise.

Free-living activity. Within a week of completing all laboratory tests, participants were monitored during their normal daily routine. This activity took place outside of the laboratory, either at the participant's place of work or at their home. Minute-by-minute HR, $\dot{V}O_2$, and motion sensor data were collected on a near-continuous basis for a 6-h period. After every 2-h period of activity, the battery pack was changed on the Cosmed K4b^2 unit, and the data were downloaded. Therefore, participants were given on average a 10-min break at each 2-h interval. During the free-living activity period, the investigator was on-site but not communicating or directly supervising the participants. During this time participants engaged in a variety of activities including, but not limited to, television viewing, general office work, reading, resistance training, walking, jogging, cooking, light cleaning, vacuuming, washing dishes, grocery shopping, and yard work.

Equipment

Portable metabolic measurement system. The Cosmed K4b^2 was used as the criterion measure for EE during laboratory and field testing. This portable indirect calorimetry unit continuously measures breath-by-breath expired gases. The Cosmed K4b^2 oxygen analyzer and carbon dioxide analyzer were calibrated immediately before each testing session in accordance with manufacturer's guidelines. At 2-h intervals during the free-living activity period, the battery pack was changed on the Cosmed K4b^2 unit, and the calibration process was repeated (a 10-min process). Data from the portable Cosmed K4b^2 were stored in memory and downloaded to a laptop computer after each test was completed. Breath-by-breath data were averaged over 1-min periods to derive $\dot{V}O_2$ values. The validity of the Cosmed K4b^2 has previously been demonstrated in our laboratory. McLaughlin et al. (15) showed that mean $\dot{V}O_2$ values measured by the Cosmed were within 0.096 $L \cdot min^{-1}$ of Douglas bag values during an incremental cycle ergometer protocol, consisting of seated rest, and 5-min stages at 50, 100, 150, 200, and 250 W.

Heart rate. The Polar Vantage NV watch is capable of storing 134 h of HR information in 1-min epochs. This watch was used for both laboratory and field testing, and was set to record in 60-s intervals. The Polar transmitter belt was attached to an elastic strap and placed around the chest. The transmitter belt's electrodes were dampened with water in accordance with manufacturer's instructions to aid in conductance. Heart rate information was downloaded and imported into a digital file after each test. Polar HR technology has been shown to be valid in both laboratory and field settings compared to electrocardiograph measurements of HR (10,11,23).

Motion sensors. The Computer Science Applications (CSA), Inc., model 7164 (Shalimar, Florida) accelerometer was used to monitor motion during free-living activity. This device is a lightweight (42 g), small (5.08 $\times$ 4.06 $\times$ 1.52 cm), lithium battery-powered accelerometer designed to measure and record acceleration and deceleration between magnitudes of 0.05 and 2 G. It is also programmed to detect movements within a frequency range of 0.25–2.5 Hz. This characteristic reduces artifact due to vibration. Acceleration and deceleration is measured in a single vertical plane over a user-specified time interval (epoch). CSA monitors were initialized 60 min before each participant began the free-living activity and were programmed to record data in 60-s epochs. Minute-by-minute data from the Cosmed K4b^2, CSA accelerometers, and the Polar HR watch were all synchronized to the same external stopwatch to ensure that all information were collected simultaneously. The CSA data were downloaded after each test and imported into a digital file.

One CSA device was attached via a Velcro strap to the posterior aspect of the dominant wrist, over the center-line of the wrist. A second CSA accelerometer was placed on the mid-axillary line of the dominant thigh, orientated vertically along the femur. An elastic bandage was used to hold the CSA monitor in place on the thigh. Calibration of the CSA accelerometers took place at the beginning and end of the study. The two CSA accelerometers were found to produce a response that met manufacturer's standards (within $\pm$ 5% of a reference value). The accelerometers were labeled so that the same device was consistently used for each body location throughout the study.

Simultaneous Heart Rate–Motion Sensor Technique

The CSA motion sensors were used to determine whether the activity performed was primarily upper- or lower-body activity. In addition, the motion sensors were used to screen out elevations in HR due to emotion or temperature. We examined thresholds of 100, 200, 300, 400, 500, and 1000 $counts \cdot min^{-1}$ relative to periods of activity and inactivity. During free-living activities a CSA value of 0–499 $counts \cdot min^{-1}$ coincided with measured EE values of 1 MET 96% of the time. A CSA value of greater than 500 $counts \cdot min^{-1}$ coincided with measured EE values of greater than 1 MET 82% of the time. Therefore, a CSA threshold of 500 $counts \cdot min^{-1}$ reflected a demarcation between rest and activity. For example, if both the leg and arm CSA counts were less than 500, we considered the individual to be at resting metabolic rate (RMR) (1 MET). If the leg $counts \cdot min^{-1}$ were 450 and the arm $counts \cdot min^{-1}$ were 1000, we used measured HR to predict EE from the corresponding arm regression equation, and *vice versa*. If both arm and leg $counts \cdot min^{-1}$ were above the 500 threshold, then we used a ratio technique between arm and leg $counts \cdot min^{-1}$ to determine whether EE should be predicted from either the arm or leg HR-$\dot{V}O_2$ regression equation. We recently demonstrated that a ratio of greater than 25 between arm and leg activity accurately reflected measured EE when using the simultaneous HR+M technique (22). Therefore, a ratio of greater than 25 between arm and leg $counts \cdot min^{-1}$ was considered to represent predominantly arm activity. It has been shown that the HR-$\dot{V}O_2$ relationship for leg activity closely represents combined arm-and-leg activity (7).

Therefore, if the arm-to-leg counts·min^{-1} ratio was less than 25, and both values were greater than 500, we predicted METs from the corresponding leg regression equation.

Flex Heart Rate

The FlexHR was established similar to the technique of Livingstone et al. (12). Before the participants completed the submaximal treadmill test, they were required to lay supine, sit, and stand for 10, 5, and 5 min, respectively. During this time, HR and $\dot{V}O_2$ were measured continuously using the Polar Vantage NV HR watch and the Cosmed K4b^2. For each individual, the FlexHR point was determined by taking the average of the highest HR during rest and the lowest HR during incremental exercise during the submaximal treadmill test. The FlexHR ranged from 83 to 101 beats·min^{-1} for our subject sample. During the 6 h of near-continuous activity, if HR was below an individual's FlexHR point, EE was assumed to be 1 MET. For HR values above individual FlexHR points, EE was predicted from individualized HR-$\dot{V}O_2$ leg regression lines.

Data Collection

During the free-living activity period some HR values were lost due to an insufficient contact between the chest strap and the participant, or interference with the telemetry signal. For this reason, we had 329 ± 21 min of HR data per participant to predict minute-by-minute EE. No $\dot{V}O_2$ or motion sensor data were lost during the free-living activity period. Absolute $\dot{V}O_2$ data (mL·min^{-1}) were converted to relative $\dot{V}O_2$ (mL·kg^{-1}min^{-1}), and these values were then divided by 3.5 to derive resting metabolic equivalents (METs).

Minute-by-minute data from the Cosmed K4b^2 and Polar HR watch were analyzed to compute the average minutes spent in resting/light (<3 METs), moderate (3–6 METs), and hard (>6 METs) activity for the 6-h period.

Statistical Analysis

For each minute, an error score was computed by subtracting the estimate of EE (simultaneous HR+M technique or FlexHR method) from the criterion measure of EE (Cosmed K4b^2) for all participants. Mean error scores were computed for time spent in resting/light, moderate, and hard activity. Values were compared with a repeated measures analysis of variance using SPSS for Windows Version 10.0.7 (SPSS Inc., Chicago, IL). *Post hoc* testing was performed with Bonferroni adjustment to locate significant differences.

Error scores were graphically illustrated via Bland-Altman plots (6) for minute-by-minute data. The shared variance was computed for both minute-by-minute predicted values of EE, and for time spent in resting/light, moderate, and hard activity, in comparison to the Cosmed K4b^2 to depict the strength of the relationship between these variables. The overall significance level was set at alpha = 0.05.

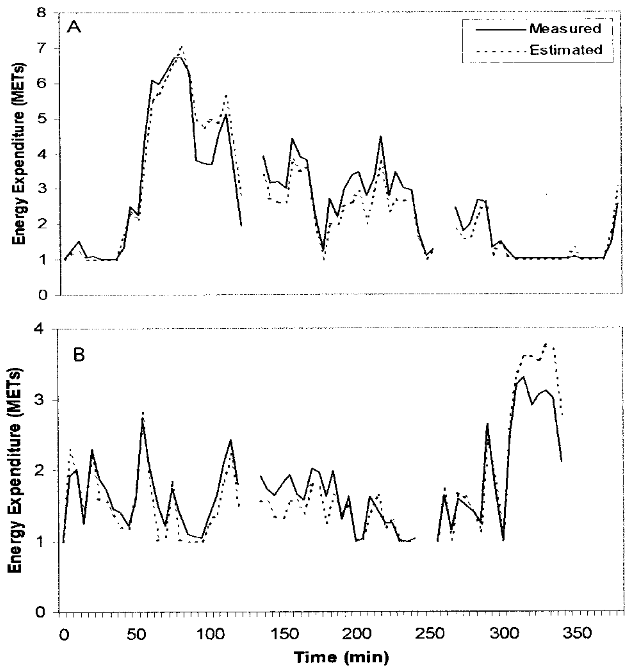

FIGURE 2—Measured (Cosmed K4b^2) versus estimated (simultaneous HR+M technique) energy expenditure for 6 h of free-living activity for two participants: (A) representative sample of different PA intensities; (B) representative sample of lower intensity activity. Breaks in monitoring represents the time the Cosmed K4b^2 was calibrated. Values represent 5-min averages.

RESULTS

The ability of the simultaneous HR+M technique to predict measured EE for a 6-h period is demonstrated for two participants in Figure 2. These participants were chosen as representative examples of individuals with periods of relatively high intensity activity for the 6-h period (Fig. 2A), and periods of relatively low intensity activity for the 6-h period (Fig. 2B). From this figure, it can be seen that the simultaneous HR+M technique is a valid method of closely tracking changes in PAEE in a field setting.

Simultaneous Heart Rate–Motion Sensor Technique

Minute-by-minute analysis. The shared variance between predicted METs from the simultaneous HR+M technique and the Cosmed was $R^2 = 0.81$ (SEE = 0.55 METs). The mean error for minute-by-minute analysis was 0.0 METs, with the 95% confidence interval (CI) ranging from +1.3 to −1.3 METs. *Post hoc* testing revealed the mean error score for the simultaneous HR+M technique was not significantly different from zero ($P = 0.916$), illustrating that this technique neither over- nor under-predicted measured EE. This relationship was similar for both men and women (data not shown). Figure 3A depicts a graphical relationship of the minute-by-minute error scores.

Total energy expenditure. We summed 6-h minute-by-minute MET values to derive an estimate of total EE. Total EE values (mean ± SD) predicted by the simultaneous

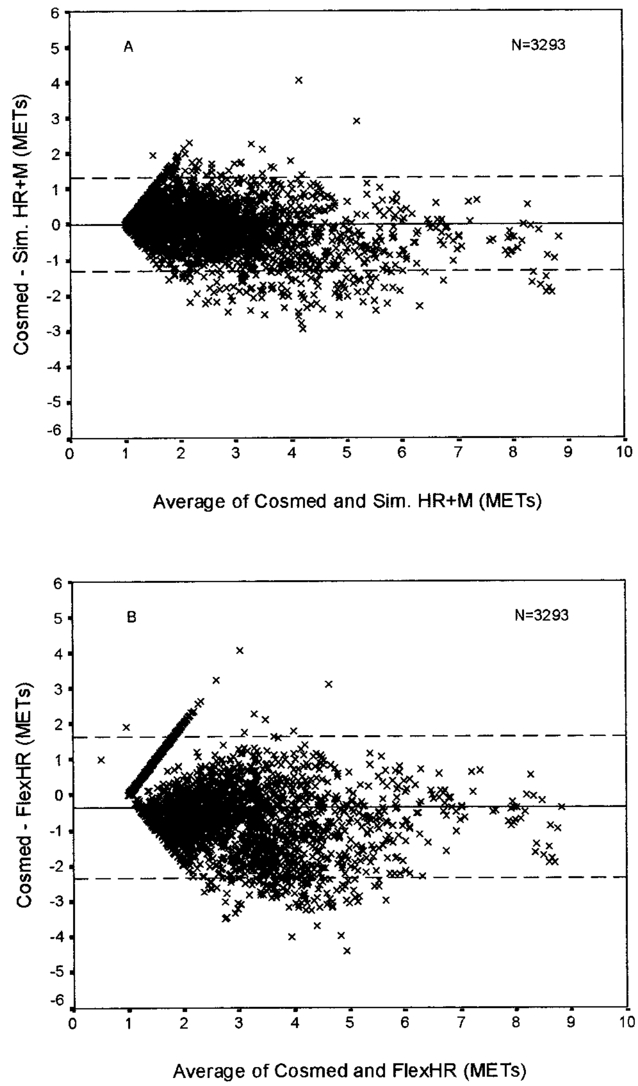

FIGURE 3—Bland-Altman plots depicting error scores for minute-by-minute energy expenditure (criterion minus estimate) for (A) the simultaneous HR+M technique and (B) the FlexHR method. The *solid line* represents the mean error, and the *dashed lines* represent the 95% confidence interval.

HR+M technique (748 ± 178 MET·min^{-1}) were not significantly different to measured values obtained by the Cosmed K4b^2 (749 ± 138 MET·min^{-1}).

Time spent in different intensities of physical activity. The mean error scores revealed that the simultaneous HR+M technique accurately predicted time spent in resting/light, moderate and hard activity ($P = 0.09$, $P = 0.13$, and $P = 0.11$, respectively) (Table 2). Figure 4 shows the mean values for time spent in resting/light, moderate, and hard activity.

Flex Heart Rate

Minute-by-minute analysis. The shared variance between predicted METs using FlexHR and Cosmed measured METs was $R^2 = 0.63$ (SEE = 0.76 METs). The mean error for minute-by-minute EE was −0.4 METs, with the 95% CI ranging from +1.6 to −2.4 METs. *Post hoc* testing revealed

TABLE 2. Mean error scores (criterion minus device) for time spent in resting/light (<3 METs), moderate (3–6 METs), and hard activity (≥6 METs) (mean ± SD).

	Mean Error Scores	
	Cosmed K4b^2 minus Sim. HR + M	Cosmed K4b^2 minus FlexHR
Min of resting/light activity	+12 ± 19	+45 ± 51*
Min of moderate activity	−9 ± 16	−38 ± 43*
Min of hard activity	−3 ± 5	−6 ± 9

* Mean error score is significantly different from zero at the 0.05 level; $N = 10$.

that the FlexHR method significantly overestimated measured minute-by-minute EE ($P < 0.0001$). This relationship was similar across genders (data not shown). Figure 3B depicts a graphical relationship of the minute-by-minute error scores.

Total energy expenditure. The 6-h total EE values predicted from the FlexHR method were significantly different from measured values by the Cosmed K4b^2 (871 ± 274 MET·min^{-1} vs 749 ± 138 MET·min^{-1}, respectively).

Time spent in different intensities of physical activity. The FlexHR method underestimated time spent in resting/light activity by 45 ± 51 min ($P = 0.02$) and

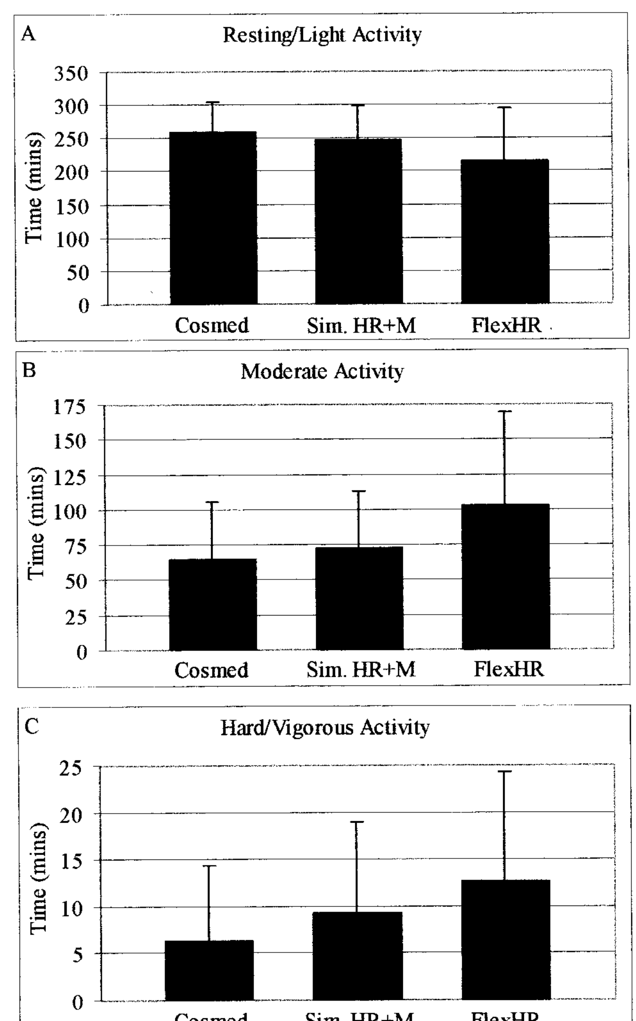

FIGURE 4—Mean values for (A) time spent in resting/light activity (<3 METs), (B) time spent in moderate activity (3–6 METs), and (C) time spent in hard activity (≥6 METs). *Bars* represent mean values ± 1 SD at each activity level.

overestimated time spent in moderate activity by 38 ± 43 min ($P = 0.02$). The FlexHR method marginally overestimated time spent in hard activity by 6 ± 9 min ($P = 0.06$) (Table 2). Overall mean values are presented in Figure 4.

DISCUSSION

In this study, we compared estimates of free-living daily activity by using the simultaneous HR+M technique and the FlexHR method to indirect calorimetry for a near-continuous 6-h period. The major finding was that arm and leg monitoring can be used to refine HR estimates of EE during free-living activity, by discriminating between upper and lower body activity, as suggested by Haskell et al. (7). The 95% CI for the simultaneous HR+M technique for minute-by-minute EE in this study was ± 1.3 METs. The level of agreement between measured EE and the simultaneous HR+M technique ($R^2 = 0.81$, SEE = 0.55 METs) is similar to the laboratory values reported by Haskell et al. (7) using this same technique ($R^2 = 0.89$, SEE = 0.66 METs).

Results from this study found that the FlexHR method resulted in a small, but significant overestimation ($P < 0.001$) of minute-by-minute EE. Although the FlexHR method attempts to screen out elevations in HR due to nonrelated activity by establishing a critical threshold, it is unable to account for the different relationship that exists between HR and $\dot{V}O_2$ for arm and leg activity, as shown in Figure 1. During the present study, participants performed an average of 56 min of arm activity, comprising 14% of the total activity. Because HR is higher for any given $\dot{V}O_2$ during arm activity compared with leg activity, this may have accounted for the FlexHR method overestimating the measured minute-by-minute EE. This significant overestimation was also apparent for total 6-h EE.

We previously demonstrated during 15-min bouts of selected lifestyle activities that using arm and leg HR-$\dot{V}O_2$ regression equations significantly improves the prediction of EE over a leg regression equation (22). We demonstrated that HR predictions of EE by using a leg regression equation overestimated measured EE by 11%. We also illustrated in our previous study that the simultaneous HR+M technique was considerably more accurate in estimating EE than a motion sensor place on the hip. CSA accelerometer and Yamax pedometer predictions of EE underestimated measured EE by 30–59%, which is in agreement with other studies examining the prediction of EE by using hip-mounted motion sensors (3,9). The reason for this underestimation is that hip-mounted motion sensors fail to account for arm work, external work involved in carrying or pushing objects, or ascending stairs.

The U.S. Surgeon General's Report and other public health organizations emphasize the importance of accumulating 30 min or more of moderate intensity activity on most, if not all, days of the week (19,24). To establish whether an individual is meeting this goal, one needs an accurate technique to assess time spent in intensity classifications. This was the reason we chose to express the data on a minute-by-minute basis rather than simply averaging the information. The simultaneous HR+M technique was found to be a valid method of assessing time spent in different PA intensity categories. In contrast, the FlexHR method was found to significantly underestimate time spent in resting/light activity and significantly overestimate time spent in moderate activity (Table 2). A visual representation of the mean values for time spent in resting/light, moderate, and hard activity can be seen in Figure 4. This figure shows that intensity classification min values predicted from the simultaneous HR+M technique have a closer relationship with indirect calorimetry, in comparison to the FlexHR method. Therefore, the simultaneous HR+M technique was able to predict PA intensity patterns with a greater degree of accuracy than the FlexHR method. Furthermore, the simultaneous HR+M technique showed a greater level of agreement than the FlexHR method for the amount of time spent in all activity categories, in comparison with indirect calorimetry (Table 3).

TABLE 3. Shared variance values (R^2) between the Cosmed K4b^2, simultaneous HR + M technique, and FlexHR method for time spent in resting/light (<3 METs), moderate (3–6 METs), and hard activity (≥6 METs).

	Prediction Methods vs Cosmed K4b^2	
	Sim. HR + M	FlexHR
Min. of resting/light activity	0.89*	0.69*
Min. of moderate activity	0.87*	0.63*
Min. of hard activity	0.79*	0.36

* Significant at the 0.01 level; $N = 10$.

This study has strengths that contribute to the understanding of measuring PAEE by using the simultaneous HR+M technique. The simultaneous HR+M technique was compared with the FlexHR method over a near-continuous time period by analyzing minute-by-minute data in relation to a criterion method for assessing free-living activity. To our knowledge, this is the first study to attempt this type of analysis. As nearly as possible, participants performed their normal daily routines. A limitation of the present study is that the Cosmed K4b^2 is somewhat intrusive, but nonetheless it provides a "gold standard" against which other methods can be compared. An additional limitation to this study was that the type and time spent in different free-living activities were not recorded. The use of a PA log may have enhanced the utility of the simultaneous HR+M technique by allowing different types of activity under free-living conditions to be described and evaluated.

As a method to predict EE, the simultaneous HR+M technique has limited application because it involves considerable data management and is extremely time consuming. However, it could be a very useful technique to validate other field-based PA assessment techniques, especially those designed to measure the time spent in moderate or vigorous activity. The simultaneous HR+M technique could also be used to document the quality and quantity of PAEE in smaller intervention studies.

In summary, our results showed that the simultaneous HR+M technique is a valid measurement tool for assessing the amount of time spent in resting/light, moderate, and hard activity. Analysis showed that this technique can accurately predict minute-by-minute EE and that it was accurate for assessing total EE over a 6-h period. This finding has important implications for the study of PA assessment. The simultaneous HR+M technique allows researchers to more accurately quantify PA intensity with a higher degree of accuracy than currently available assessment measures of free-living activity.

The authors wish to acknowledge Dr. Edward T. Howley for his helpful comments in preparing this manuscript. This work was supported in part by a grant from the American College of Sports Medicine (ACSM)–Polar Research Grant on Controlled Heart Zone Exercise. The opinions expressed herein are those of the authors and do not necessarily represent the views of the ACSM or Polar Electro, Kempele, Finland. The use of trade names and commercial sources in this document is for the purposes of identification only, and does not imply endorsement.

Address for correspondence: Scott J. Strath, PhD, Dept. PM&R, University of Michigan, 1500 E. Medical Center Drive, MPB D4113, Ann Arbor, MI 48109-0718; E-mail: sstrath@med.umich.edu.

REFERENCES

1. American College of Sports Medicine. The recommended quantity and quality of exercise for developing and maintaining cardiorespiratory and muscular fitness in healthy adults. *Med. Sci. Sports Exerc.* 22:265–274, 1996.
2. American Heart Association. Statement on exercise: benefits and recommendations for physical activity programs for all Americans. *Circulation* 94:857–862, 1996.
3. Bassett, D. R., Jr., B. E. Ainsworth, A. M. Swartz, et al. Validity of four motion sensors in measuring moderate intensity physical activity. *Med. Sci. Sports Exerc.* 32:S471–S480, 2000.
4. Bijnen, F. C., C. J. Casperson, and W. L. Mosterd. Physical inactivity as a risk factor for coronary heart disease: A World Health Organization and International Society and Federation of Cardiology position statement. *Bull. W.H.O.* 72:1–4, 1994.
5. Blair, S. N. Physical activity, physical fitness, and health. *Res. Q. Exerc. Sport* 64:365–376, 1993.
6. Bland, J. M., and D. G. Altman. Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet* 338:1622–1623, 1986.
7. Haskell, W. L., M. C. Yee, A. Evans, and P. J. Irby. Simultaneous measurement of heart rate and body motion to quantitate physical activity. *Med. Sci. Sports Exerc.* 25:109–115, 1993.
8. Helmrich, S. P., D. R. Ragland, R. W. Leung, and R. S. Paffenbarger, Jr. Physical activity and reduced occurrence of non-insulin dependent diabetes mellitus. *N. Engl. J. Med.* 325:147–152, 1991.
9. Hendelman, D., K. Miller, C. Bagget, E. Debold, and P. Freedson. Validity of accelerometry for the assessment of moderate intensity physical activity in the field. *Med. Sci. Sports Exerc.* 32:S442–S449, 2000.
10. Karvonen, J., J. Chwalbinska-Moneta, and S. Saynajakangas. Comparison of heart rates measured by ECG and microcomputer. *Phys. Sports Med.* 12:65–69, 1984.
11. Leger, L., and M. Thivierge. Heart rate monitors: validity, stability, and functionality. *Phys. Sports Med.* 16:143–151, 1988.
12. Livingstone, M. B. E., A. M. Prentice, W. A. Coward, et al. Simultaneous measurement of free-living energy expenditure by the doubly labeled water method and heart rate monitoring. *Am. J. Clin. Nutr.* 52:59–65, 1990.
13. Luke, A., K. C. Maki, N. Barkey, R. Cooper, and D. Mcgee. Simultaneous monitoring of heart rate and motion to assess energy expenditure. *Med. Sci. Sports Exerc.* 29:144–148, 1997.
14. Manson, J. E., D. M. Nathan, A. S. Krolewski, et al. A prospective study of exercise and incidence of diabetes among U.S. male physicians. *JAMA* 268:63–67, 1992.
15. Mclaughlin, J. E., G. A. King, E. T. Howley, D. R. Bassett, Jr., and B. E. Ainsworth. Validation of the Cosmed K4b^2 portable metabolic system. *Int. J. Sports Med.* 22:280–284, 2001.
16. Morris, J. N., D. G. Clayton, M. G. Everitt, A. M. Semmence, and E. H. Burgess. Exercise in leisure time: coronary attack and death rates. *Br. Heart J.* 63:325–334, 1990.
17. Paffenbarger, Jr., R. S., A. L. Wing, R. T. Hyde, and D. L. Jung. Physical activity and incidence of hypertension in college alumni. *Am. J. Epidemiol.* 117:245–257, 1983.
18. Paffenbarger, Jr., R. S, R. Hyde, A. Wing, and C. Hsieh. Physical activity, all-cause mortality, and longevity of college alumni. *N. Engl. J. Med.* 314:605–613, 1986.
19. Pate, R., M. Pratt, S. Blair, et al. Physical activity and public health. *JAMA* 273:402–407, 1995.
20. Shaper, A. G., and G. Wannamethee. Physical activity and ischaemic heart disease in middle-aged British men. *Br. Heart J.* 66:384–394, 1991.
21. Shaper, A. G., G. Wannamethee, and M. Walker. Physical activity, hypertension and risk of heart attack in men without evidence of ischaemic heart disease. *Br. Heart J.* 8:3–10, 1994.
22. Strath, S. J., D. R. Bassett, Jr., A. M. Swartz, and D. L. Thompson. Simultaneous heart rate-motion sensor technique to estimate energy expenditure. *Med. Sci. Sports Exerc.* 33:2118–2123, 2001.
23. Treiber, F. A., L. Musante, S. Hartdagan, H. Davis, M. Levy, and W. B. Strong. Validation of a heart rate monitor with children in laboratory and field settings. *Med. Sci. Sports Exerc.* 21:338–342, 1989.
24. 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 for Disease Control and Prevention, National Center for Chronic Disease Prevention and Health Promotion, 1996, pp. 3–6.