Simultaneous heart rate-motion sensor technique to estimate energy expenditure

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ABSTRACT

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.*, Vol. 33, No. 12, 2001, pp. 2118–2123. **Purpose:** Heart rate (HR) and motion sensors represent promising tools for physical activity (PA) assessment, as each provides an estimate of energy expenditure (EE). Although each has inherent limitations, the simultaneous use of HR and motion sensors may increase the accuracy of EE estimates. The primary purpose of this study was to establish the accuracy of predicting EE from the simultaneous HR-motion sensor technique. In addition, the accuracy of EE estimated by the simultaneous HR-motion sensor technique was compared to that of HR and motion sensors used independently. **Methods:** Thirty participants (16 men: age, 33.1 ± 12.2 yr; BMI, 26.1 ± 0.7 $kg \cdot m^{-2}$; and 14 women: age, 31.9 ± 13.1 yr; BMI, 27.2 ± 1.1 $kg \cdot m^{-2}$ (mean ± SD)) performed arm and leg work in the laboratory for the purpose of developing individualized HR-$\dot{V}O_2$ regression equations. Participants then performed physical tasks in a field setting for 15 min each. CSA accelerometers placed on the arm and leg were to discriminate between upper and lower body movement, and HR was then used to predict EE (METs) from the corresponding arm or leg laboratory regression equation. A hip-mounted CSA accelerometer and Yamax pedometer were also used to predict EE. Predicted values (METs) were compared to measured values (METs), obtained via a portable metabolic measurement system (Cosmed K4b^2). **Results:** The Yamax pedometer and the CSA accelerometer on the hip significantly underestimated the energy cost of selected physical activities, whereas HR alone significantly overestimated the energy cost of selected physical activities. The simultaneous HR-motion sensor technique showed the strongest relationship with $\dot{V}O_2$ ($R^2 = 0.81$) and did not significantly over- or underpredict the energy cost ($P = 0.341$). **Conclusion:** The simultaneous HR-motion sensor technique is a good predictor of EE during selected lifestyle activities, and allows researchers to more accurately quantify free-living PA. **Key Words:** PHYSICAL ACTIVITY, OXYGEN UPTAKE, EXERCISE, PEDOMETER, ACCELEROMETER

Numerous epidemiological studies have reported inverse relationships between physical activity (PA), assessed by questionnaire, and selected disease outcomes such as coronary artery disease, hypertension, diabetes mellitus, and some cancers (8,12,16,20–23). Although PA questionnaires are acceptable for recalling structured exercise, significant error may occur because of inaccuracy in recall of ubiquitous, light, or moderate intensity PA (18). Consequently, questionnaires may not truly reflect one's level of PA accumulated throughout the day during lifestyle activities (2,24). Therefore, more accurate and reliable methods for estimating PA in free-living individuals are required to generate greater clarity of the role of PA as a factor relating to human health.

The potential for using heart rate (HR) and motion sensors to assess PA and daily energy expenditure (EE) has been discussed elsewhere (3,5,9,14,18). Although each method can provide an estimate of EE, there are inherent limitations to their individual use. HR is a physiological variable that closely reflects changes in PA intensity; however, it is influenced by factors such as activity mode, emotion, posture, environmental conditions, and fitness level (10). Electronic motion sensors, typically placed on the hip, are growing in popularity, but are unable to detect arm movements, or the external work done in lifting or pushing objects, which may represent a considerable component of lifestyle activity (3). It has been proposed that the simultaneous use of HR and motion sensors may increase the accuracy of EE prediction and overcome some of their individual limitations (7,15,19,25). Haskell et al. (7) proposed 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 the $\dot{V}O_2$ from the corresponding regression equation. With the development of valid portable metabolic measurement systems (17), this important question can be fully explored within a field setting.

Therefore, the primary purpose of this study was to test the accuracy of predicting EE from the simultaneous HR-motion sensor technique over a wide range of lifestyle activities. A secondary purpose was to compare EE obtained by this technique with EE estimated from HR and motion sensors independently.

METHODS

Thirty participants, 16 men and 14 women, were recruited from the Knoxville, Tennessee, area to take part in this

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TABLE 1. Descriptive characteristics of the study participants (mean ± SD).

	Men (N = 16)	Women (N = 14)	All (N = 30)
Age (yr)	33.1 ± 12.2	31.9 ± 13.1	32.5 ± 12.7
Height (cm)	176.3 ± 8.4	163.5 ± 14.2	170.0 ± 11.3
Weight (kg)	79.6 ± 9.1	60.7 ± 6.4	70.2 ± 7.8
BMI (kg · m^{-2})	26.1 ± 0.7	27.2 ± 1.1	26.7 ± 0.9

study. Individuals were recruited from within the university and surrounding community through public announcements and word of mouth. In an effort to obtain results generalizable to the U.S. population, participants within an age range of 18–60 yr, including ethnic minorities, were included for participation (80% Caucasian, 17% African American, and 3% Hispanic). Each participant read and signed an informed consent form approved by the University of Tennessee Institutional 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 weight measured using a calibrated physician's scale (Health-O-Meter, Bridgeview, IL), and their height measured using a stadiometer (Seca Corp., Columbia, MD). The physical characteristics of the participants are listed in Table 1.

Experimental Protocols

Submaximal treadmill test. Participants walked on a treadmill (Q65, Quinton Instrument Co., Bothell, WA) following a modified Balke-type 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 subject reached 80–85% of their age-predicted maximal HR.

Submaximal arm ergometer test. Participants performed successive 3-min stages on a Monark arm ergometer (Monark 881E, Varberg, Sweden). The initial cadence was set at 50 rpm, and initial resistance at 0 kiloponds (Kp). Thereafter, cadence remained constant and resistance increased 0.25 Kp every stage. The test was terminated once the participant reached 80–85% of their age-predicted maximal HR, or they requested to stop. Five participants (four women and one man) requested to stop at 69, 71, 72, 76, and 77% of their age-predicted maximal HR, respectively.

Lifestyle activity. Activities were chosen to represent a wide range of experiences, using primarily arm, primarily leg, or combined arm and leg motion. HR, $\dot{V}O_2$, and motion sensor data were collected continuously throughout each activity. Participants performed each activity for 15 min. Eleven participants performed the housework activities (six men, five women), nine performed the yardwork activities (five men, four women), and 10 performed the conditioning activities (five men, five women). The specific activities are listed below:

1. Housework: Vacuuming, scrubbing floors, ironing, washing windows, washing dishes, and light cleaning.
2. Yardwork: Power mowing, raking, trimming, and general gardening.
3. Conditioning: Slow walking, brisk walking, walking with intermittent stair climbing, and dumbbell exercises.

Portable Metabolic Measurement System

The Cosmed K4b^2 (Cosmed, S.r.L, Rome, Italy) is a portable indirect calorimeter that continuously measures expired gases. It has been shown to be a valid instrument for the measurement of $\dot{V}O_2$ (17), and hence EE. McLaughlin et al. (17) showed that the $\dot{V}O_2$ values measured by the Cosmed K4b^2 were within 0.096 L·min^{-1} of Douglas bag values during a continuous incremental cycle ergometer protocol, consisting of seated rest, and 5-min stages at 50, 100, 150, 200, and 250 W. This portable unit was calibrated in accordance with the manufacturer's instructions and was used throughout all testing protocols and activities to derive measurements of $\dot{V}O_2$.

Heart Rate

The Polar Vantage XL (Polar Electro, Kempele, Finland) was used to assess HR throughout all testing protocols and activities. This HR watch has been shown to be valid in both laboratory and field settings relative to electrocardiograph measurements of HR (11,13,26).

Motion Sensors

The Computer Science Applications (CSA), Inc., model 7164 (Shalimar, FL) accelerometers were used to monitor motion during the lifestyle activities. Three CSA motion sensors were utilized. One was placed on the dominant wrist oriented along the axis of the forearm. Velcro fasteners were used to attach the CSA monitor to the wrist. A second CSA monitor was placed on the hip in accordance with the manufacturer's instructions. The hip CSA was placed in a nylon pouch (manufacturer-supplied) and affixed to the hip via a belt. The third CSA accelerometer was placed on the lateral aspect of the right thigh, on the midaxillary line, orientated vertically along the femur. An elastic bandage was used to hold the CSA monitor in place on the thigh. In addition to the CSA accelerometers, an electronic pedometer (Yamax SW-701, Tokyo, Japan) was affixed in accordance to the manufacturer's instructions to the hip via a belt.

Data Collection

Heart rate, $\dot{V}O_2$, and motion sensor data were recorded every minute throughout submaximal exercise and lifestyle activity protocols. Participants performed each lifestyle activity for 15 min. Each activity was preceded with 5 min of sitting rest. The data recorded between minutes 5–15 of each lifestyle activity were averaged to obtain mean HR, $\dot{V}O_2$, and CSA values. 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 convert them into METs (resting metabolic equivalents).

The CSA measures activity with a single-channel accelerometer that records accelerations ranging in magnitude from 0.05 to 2 G. The device is programmed to detect a

TABLE 2. Measured and predicted energy expenditure requirements (METs), percent of age-predicted maximal heart rate, and Compendium values for selected activities: values reflect means and standard deviations (SD).

	Measured METs	Yamax METs	CSA METs	HR METs	Sim HR-M METs	$\%HR_{max}$ [a]	Compendium [b]	
							METs	Code
Vacuuming	3.9 (0.6)	1.4 (0.3)	2.3 (0.4)	4.1 (0.8)	3.7 (0.8)	30.9 (8.2)	3.5	05043
Cleaning	3.0 (0.8)	1.4 (0.3)	2.2 (0.5)	2.9 (0.6)	2.9 (0.7)	21.6 (6.3)	3.0	05030
Scrubbing floors	3.3 (0.5)	1.1 (0.1)	2.3 (0.3)	4.0 (0.8)	3.2 (0.8)	25.3 (7.3)	3.8	05130
Washing dishes	2.1 (0.5)	1.1 (0.1)	1.6 (0.2)	2.6 (0.7)	2.0 (0.5)	18.3 (8.4)	2.3	05041
Window washing	3.0 (0.6)	1.3 (0.4)	1.7 (0.2)	3.3 (0.5)	3.0 (0.6)	28.5 (6.1)	3.0	05020
Ironing	2.1 (0.4)	1.1 (0.1)	1.5 (0.1)	2.5 (0.6)	1.9 (0.7)	15.7 (8.0)	2.3	05070
Slow walk (average, 72 $m \cdot min^{-1}$)	3.2 (0.6)	4.1 (1.3)	3.0 (1.0)	3.3 (0.9)	3.3 (0.9)	35.6 (5.6)	3.0	17170
Brisk walk (average, 107 $m \cdot min^{-1}$)	5.0 (1.1)	7.1 (1.6)	5.2 (0.9)	5.1 (1.2)	5.1 (1.2)	46.3 (11.5)	5.0	17220
Weight circuit	2.8 (0.8)	1.1 (0.2)	1.5 (0.1)	5.8 (0.5)	3.1 (0.6)	44.2 (7.3)	3.0	02130
Stair climbing/walking	6.1 (1.5)	6.4 (1.2)	4.4 (0.9)	6.4 (1.3)	6.4 (1.3)	47.6 (13.7)	N/A	N/A
Power mowing	5.6 (0.7)	3.0 (0.7)	4.2 (1.0)	6.3 (0.9)	6.3 (0.9)	52.4 (12.0)	5.5	08120
Gardening	3.6 (1.1)	1.7 (0.4)	2.4 (0.6)	3.6 (1.0)	3.6 (1.0)	27.4 (12.4)	4.0	08245
Manual trimming	4.2 (0.6)	1.4 (0.2)	1.9 (0.5)	5.2 (1.0)	4.0 (0.8)	46.4 (13.5)	4.5	08210
Raking	3.9 (0.8)	1.5 (0.3)	2.0 (0.4)	4.6 (1.2)	4.0 (1.2)	45.3 (16.4)	4.3	08160

[a] Percent of age-predicted maximal HR.

[b] Compendium MET values and corresponding activity codes taken from Ainsworth et al. (1).

frequency response from 0.25 to 2.5 Hz, so as to discard movements caused by vibration. An analog-to-digital converter quantifies the magnitude of the acceleration, establishing a linear response to accelerations. These values are then integrated over a user-specified time interval (epoch). Sixty-second epochs were specified. The three CSA accelerometers were synchronized to the same external timepiece to ensure that data from the Cosmed $K4b^2$, data from the accelerometers, data from the pedometer, and HR data were collected simultaneously. All CSA data was downloaded after each test and imported into a digital file. Average counts per minute were calculated from minutes 5–15. Average values from the CSA placed on the hip were used to determine estimates of gross EE (METs) using the regression equation of Freedson et al. (6).

The Yamax pedometer provided estimates of EE in kilocalories. The participant's body weight was entered and an assumed stride length (2.5 ft (76 cm)) was input into the pedometer. The Yamax was reset to zero immediately before each activity, and after 15 min of data collection the cumulative value was recorded. The cumulative EE value for the 15 min of activity was divided by 15 to obtain a mean EE value in kilocalories per minute. Kilocalorie values were transformed into METs using standard constants ($1\ L\ O_2 = 4.8$ kcal, $1\ MET = 3.5\ mL \cdot kg^{-1} \cdot min^{-1}$). Yamax values were assumed to represent net EE and were converted to gross EE. To account for the added weight of the Cosmed $K4b^2$ unit and motion sensors worn by the individual, 1 kg was added to the measured body weight in all calculations.

Statistical Analysis

For each activity performed by a participant, an error score was computed by subtracting the estimate (HR, belt-mounted motion sensors worn on the hip, simultaneous HR-motion sensor technique) from the criterion (Cosmed $K4b^2$). The mean error scores for each of the techniques were compared using a repeated measures analysis of variance using SPSS for Windows version 10.0.0 (SPSS, Inc., Chicago, IL). *Post hoc* testing was performed with Bonferroni adjustment to locate significant differences. The overall significance level was set at alpha = 0.05.

Error scores were graphically illustrated via Bland-Altman plots (4). In addition, linear regression analysis was performed for all measures of EE, to depict the strength of the relationship between these variables.

RESULTS

Table 2 shows the mean (± SD) values for METs determined from the Cosmed $K4b^2$ for each activity. The mean MET range for all 14 activities was 2.1 to 6.1 METs, thus incorporating light-, moderate-, and some hard-intensity activities. The mean MET values for all activities are also shown for the Yamax, CSA, HR, and the simultaneous HR-motion sensor technique. The mean range for percent of age-predicted maximal HR indicated that the participants were working between 15.7 and 52.4% of their relative capacity. The MET values from the updated Compendium of Physical Activities (1) are given for comparison purposes. All mean measured values were found to be in close agreement with those listed in the Compendium, falling within ± 1 SD.

The individual HR-$\dot{V}O_2$ data collected during both submaximal exercise protocols were used to develop individualized regression equations. The treadmill component represented leg exercise, whereas the arm ergometer component represented arm exercise. Data from the individualized regression analysis for each activity were combined to show the different relationship between HR and $\dot{V}O_2$ for arm and leg exercise (Fig. 1). We chose not to examine combined arm and leg activity, as this has been shown to closely reflect the legs-only condition (7).

Yamax SW-701 electronic pedometer. The relationship between predicted METs from the electronic pedometer and measured METs from the Cosmed $K4b^2$ was $R^2 = 0.36$ for all participants (Table 3). The shared variance for men was $R^2 = 0.29$, and for women was $R^2 = 0.41$ (data not shown). The Yamax pedometer significantly underestimated the measured EE by an average of 1.2 METs, or 59.2%, as shown in Figure 2A ($P < 0.001$). The extent of the underestimation was the same for men and women (1.2 METs, data not shown).

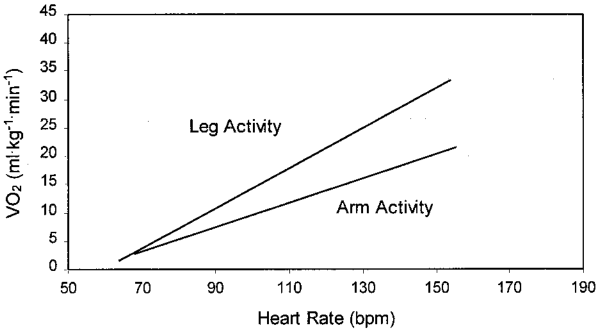

FIGURE 1—The relationship between HR and measured oxygen uptake during treadmill walking and arm ergometer exercise.

CSA hip-mounted accelerometer. The strength of the relationship between MET values predicted from the CSA accelerometer on the hip (using the regression equation of Freedson et al. (6)) and measured METs from the Cosmed K4b^2 was $R^2 = 0.54$ for all participants (Table 3). The shared variance for men was $R^2 = 0.45$, and for women was $R^2 = 0.69$ (data not shown). The CSA significantly underestimated the measured MET values by an average of 1.1 METs, or 29.5%, as shown in Figure 2B ($P < 0.001$). The extent of the underestimation was similar for men and women, 1.0 METs (27.6%) and 1.2 METs (31.4%), respectively (data not shown).

Heart rate. Predicted METs were obtained using the individual HR-$\dot{V}O_2$ relationship obtained during the treadmill test. The strength of the relationship between the HR method and measured METs from the Cosmed K4b^2 was $R^2 = 0.67$ for all participants (Table 3). The shared variance for men was $R^2 = 0.53$, and for women was $R^2 = 0.77$ (data not shown). The HR method significantly overestimated the measured EE by an average of 0.4 METs, or 11.1%, as shown in Figure 2C ($P < 0.001$). The extent of the overestimation was similar for men and women, 0.3 METs (9.6%) and 0.5 METs (11.1%), respectively (data not shown).

Simultaneous HR-motion sensor technique. The motion sensors were used to determine whether predominately arm or leg exercise was taking place by using a ratio between the arm and leg CSA counts. A ratio of greater than or equal to 25 was used to reflect arm work, whereas a ratio of less than 25 represented leg work. For example, when the arm CSA recorded 4500 counts and the leg CSA recorded 165 counts, the ratio between arm and leg motion was 27.3. Thus, the ratio was greater than 25, illustrating that predominately arm exercise was taking place; therefore, we used the arm regression equation to predict METs for that particular activity. If the ratio was less than 25, we predicted METs from the leg regression equation. The strength of the relationship between predicted MET values from the simultaneous HR-motion sensor technique and measured MET values from the Cosmed K4b^2 was $R^2 = 0.81$ for all participants (Table 3). The shared variance for men was $R^2 = 0.71$ and for women was $R^2 = 0.89$ (data not shown). The simultaneous HR-motion sensor technique showed a significantly higher relationship with $\dot{V}O_2$ for all participants than HR alone ($P < 0.001$), the hip-mounted CSA ($P < 0.001$), and the Yamax pedometer ($P < 0.001$). The simultaneous HR-motion sensor method did not significantly over- or underpredict measured EE (0.1 METs, Fig. 2D ($P = 0.341$)). This relationship was the same for both men and women (0.1 METs, data not shown).

DISCUSSION

One of the findings of this study was that the Yamax pedometer and the CSA accelerometer placed on the hip underestimated the energy cost of selected physical activities by slightly more than 1 MET (see Fig. 2A and B). Motion sensors used independently have a number of limitations. For instance, motion sensors worn on the hip are unable to differentiate between walking on the flat versus up or down hills or stairs, and also fail to account for upper body activity. These limitations greatly affect the ability of motion sensors to accurately predict EE. The underestimation noted in this study for predicting EE from hip-worn motion sensors is consistent with previous research examining the accuracy of estimating EE using these devices (3,9). Results from this study also indicate that the HR method resulted in a small but significant overestimation (0.4 METs; Fig. 2C). This is because of a different relationship between HR and $\dot{V}O_2$ when a significant amount of upper body work is taking place. More specifically, HR will be higher for any given $\dot{V}O_2$ during arm activity in comparison with leg activity, or combined arm and leg activity. This is primarily because of the smaller amount of muscle mass involved with arm-only activity. The difference in the relationship between HR and $\dot{V}O_2$ for arm and leg activity is shown in Figure 1. Although Figure 1 highlights the different relationship between arm and leg work using group regression data, individualized data were used for predicting EE. Using a group regression equation for arm and leg activity would have introduced greater error, as other investigators have shown (7,15). Individualized HR-$\dot{V}O_2$ regression equations provide greater accuracy, as they account for individual levels of fitness.

New information from this study indicates that the simultaneous use of HR and motion sensors provides a more accurate prediction of EE in the field setting compared with the use of HR or motion sensors independently. Arm and leg activity monitoring can, therefore, be used to refine HR estimates of metabolic EE during lifestyle activities, by differentiating between upper and lower body work. This differentiation allows the investigator to predict EE on the basis of an individualized arm or leg HR-$\dot{V}O_2$ regression equation. The results from this study show that the simultaneous HR-motion sensor technique neither under- nor overpredicted measured $\dot{V}O_2$ values. The range of error (95% CI) for the simultaneous HR-motion sensor technique was within ± 1.5 METs. These results were a significant improvement over using either assessment tool independently, as shown in Figure 2. Although not tested in this study, another advantage of the simultaneous technique is

TABLE 3. Shared variance (R^2) values between various methods of obtaining METs during physical activities in field settings.

	Cosmed	CSA	Yamax	HR	Simultaneous HR-Motion Sensor
Cosmed	1.000				
CSA	0.536[a]	1.000			
Yamax	0.360[a]	0.669[a]	1.000		
HR	0.667[a]	0.349[a]	0.227[a]	1.000	
Simultaneous HR-motion sensor	0.810[a]	0.536[a]	0.353[a]	0.869[a]	1.000

[a] Significant at the $P < 0.01$ level.

that the motion sensors can differentiate between an increase in HR caused by PA and that caused by other influences such as emotion. A limitation to the present study was that it was only carried out over selected activities for a relatively short period of time. Additional validation studies are needed to determine whether this dual technology can accurately estimate EE over an extended period of time, and across a broader range of activities.

In summary, our results found that the simultaneous HR-motion sensor technique was an accurate predictor of EE during selected field-based activities of varying intensities. In light of these results, this technique warrants

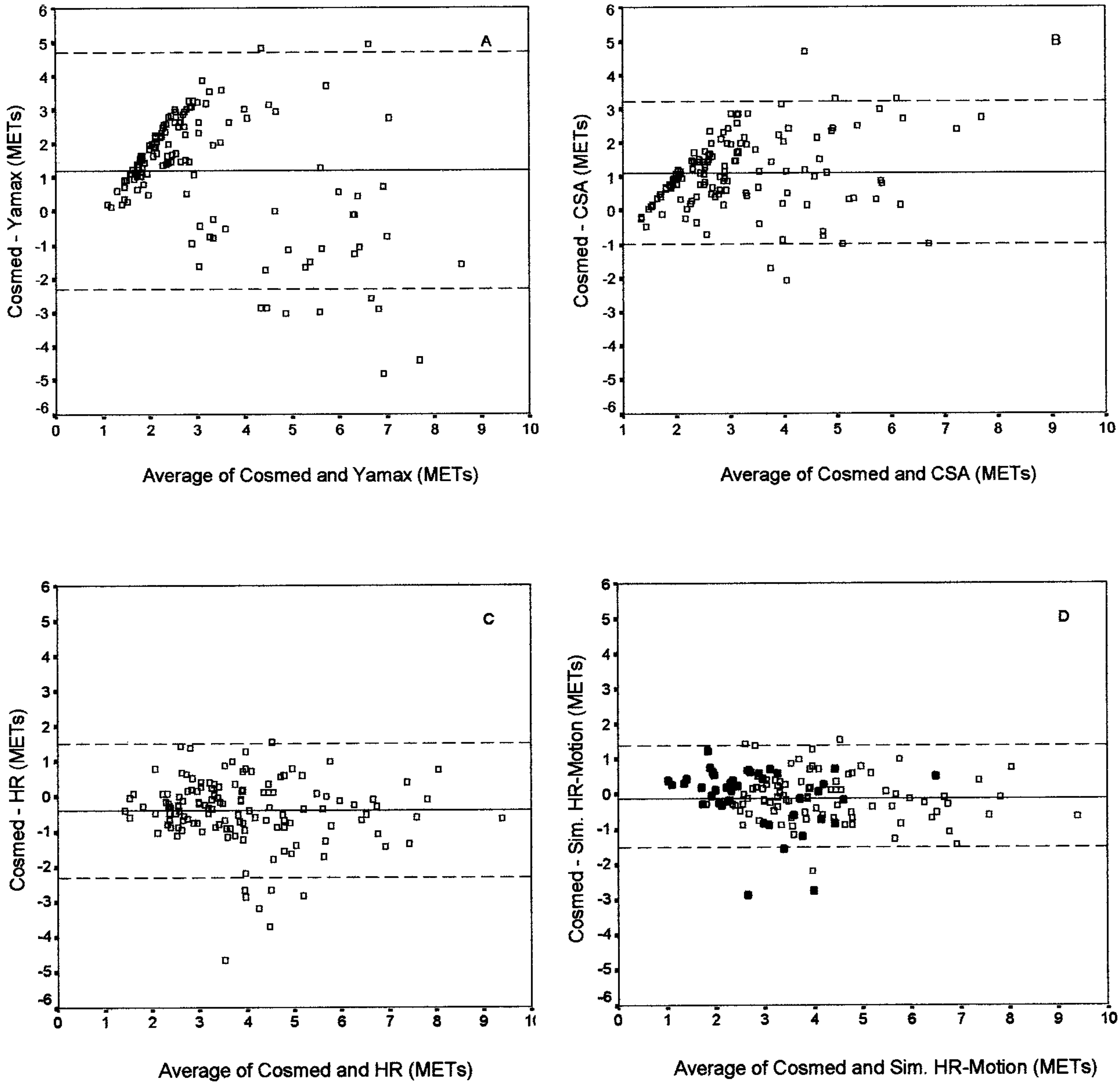

FIGURE 2—Bland-Altman plots depicting error scores for energy expenditure (criterion minus estimate) for (A) the Yamax pedometer, (B) the CSA hip accelerometer, (C) HR, and (D) the simultaneous HR-motion sensor technique, in METs. Closed data points in panel D (*filled squares*) indicate MET values predicted from individualized arm regression equations. Open data points in panel D (*open squares*) indicate MET values predicted from individualized leg regression equations. The *solid line* represents the mean, and the *dashed lines* represent the 95% confidence intervals.

further exploration as a tool for assessing habitual PA in free-living individuals.

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