Validity of a Multi-Sensor Armband in Estimating Rest and Exercise Energy Expenditure

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ABSTRACT

FRUIN, M. L., and J. WALBERG RANKIN. Validity of a Multi-Sensor Armband in Estimating Rest and Exercise Energy Expenditure. *Med. Sci. Sports Exerc.*, Vol. 36, No. 6, pp. 1063–1069, 2004. The SenseWear™ Armband (SWA; BodyMedia, Inc.), using multiple sensors, was designed to estimate energy expenditure (EE) in free-living individuals. **Purpose:** To examine the reliability and validity of the SWA during rest and exercise compared with indirect calorimetry (IC). **Methods:** EE was assessed with SWA and IC in 13 males during two resting and one cycle ergometry (40 min at 60% $\dot{V}O_{2peak}$) sessions. In a second experiment, 20 adults walked on a treadmill for 30 min at three intensities (80.5 m·min^{-1}, 0% grade; 107.3 m·min^{-1}, 0% grade; 107.3 m·min^{-1}, 5% grade) while IC and SWA measured EE. **Results:** At rest, no significant differences were found between EE measurements from the SWA (1.3 ± 0.1 kcal·min^{-1}) and IC (1.3 ± 0.1 kcal·min^{-1}), and the two methods were highly correlated ($r = 0.76$; $P < 0.004$). The SWA EE estimation was reliable when comparing the two resting visits ($r = 0.93$; $P < 0.001$). For the ergometer protocol, no significant differences were found between the SWA and IC measurements of EE early, mid, or late in exercise or for the total bout, although the measurements were poorly correlated ($r = 0.03$–0.12). The SWA EE estimate of walking increased with treadmill speed but not with incline. The SWA significantly overestimated (13–27%) the EE of walking with no grade ($P < 0.02$) and significantly underestimated (22%) EE on the 5% grade ($P < 0.002$). The SWA estimation of EE correlated moderately with IC ($r = 0.47$–0.69). **Conclusion:** The SWA provided valid and reliable estimates of EE at rest and generated similar mean estimates of EE as IC on the ergometer; however, individual error was large. The SWA overestimated the EE of flat walking and underestimated inclined walking EE. **Key Words:** SENSEWEAR™ ARMBAND, PHYSICAL ACTIVITY, CALORIC EXPENDITURE, ACTIVITY MONITORING, MOTION SENSORS

Population-based surveys demonstrate that most adults in the United States are inactive (18). It is commonly believed that the modern inactive lifestyles of Americans are contributing to the obesity epidemic (6,14). One study of over 19,000 men showed that those who increased their vigorous activity over a 4-yr period lost weight whereas those with sedentary lifestyles gained weight (4). Thus, it would be valuable to accurately determine baseline activity for individuals as well as change in quantity of activity in order to aid in determining risk of chronic disease and efficacy of various interventions, but this is not easily measured.

Doubly labeled water (DLW) and indirect calorimetry techniques—the gold standard measures of energy expenditure (20)—are both limited in their assessment of free-living energy expenditure. Indirect calorimetry cannot easily assess free-living subjects, whereas DLW does not provide information on the pattern or intensity of physical activity. Furthermore, the expense of the equipment and supplies, time needed in the laboratory and for subsequent analysis, burden for subjects, and significant amount of technical expertise required limit the use of these techniques (2). Other physical activity and energy expenditure assessment tools have been developed to provide simpler, more cost-effective estimates. Physical activity records and questionnaires provide a convenient, low-cost estimation of physical activity and/or energy expenditure; however, over- or underestimation is typically significant (mean ranging from 8 to 62%) (5,10,17) and assessment of individual physical activity is often poor, demonstrated by wide limits of agreement on bias plots or lack of correlation between the estimation and criterion measures (5,17).

To improve on the subjective nature of physical activity records and questionnaires, objective tools (e.g., heart rate monitors, pedometers, accelerometers) have been developed. There is some evidence that triaxial accelerometers, which detect body acceleration in three planes, may offer the most promise compared with other activity monitors available in assessing free-living physical activity energy expenditure (10,21). However, triaxial accelerometer estimates of energy expenditure during locomotion typically overestimate (12–49%) the measurements made by indirect calorimetry (2,13,19). Not only have triaxial accelerometers been found to overestimate the energy expenditure of walking and running, they have been found to significantly underestimate the energy cost of walking up an incline by

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8–21% (9,11,13), cycling exercise by 53–68% (2,9), and performing activities of daily living by 35–45% (10,19). Nonetheless, these devices provide an objective measure, are lightweight, provide minimal disruption to normal activities, and are able to record data continuously over long periods of time.

A new device with similar user-friendly characteristics, the SenseWear™ Armband (SWA; BodyMedia, Inc., Pittsburgh, PA), is worn on the upper arm and collects a variety of physiologic data through multiple sensors (a two-axis accelerometer, heat flux sensor, skin temperature sensor, near-body ambient temperature sensor, and galvanic skin response sensor) that can be uploaded and analyzed using computer software. The multiple sensor array was designed to overcome the limitations of other objective energy expenditure assessment tools; however, no studies have been published in the scientific literature concerning the reliability or validity of this device. The primary purpose of this investigation was to examine the validity of the SenseWear™ Armband's energy expenditure estimation at rest and with two modes of exercise in a laboratory setting compared with simultaneous indirect calorimetry measurements.

METHODS

All procedures for experiment 1 and 2 were approved by the Human Subjects Institutional Review Board of Virginia Tech. Subjects for both studies completed a health history form and provided informed consent before participating. Height and weight were measured and body fat was estimated, using a three-site skin fold measurement and body density equation (7,8), on all subjects.

Experiment 1. Thirteen 18- to 25-yr-old normal weight males (Table 1) were recruited for the study. All participants were healthy nonsmokers and aerobically untrained ($\leq$3 d of structured aerobic exercise per week). Aerobic fitness or peak oxygen consumption ($\dot{V}O_{2peak}$) was determined using a graded exercise test on a cycle ergometer (Monark 818E Ergomed C) with continuous indirect calorimetry measurement (SensorMedics Vmax 229, Yorba Linda, CA). After a brief warm-up, the subject began the test at 60 W (1 kp, 60 rpm) and intensity increased 20 W (1/3 kp) every minute until exhaustion, which was determined when the subject failed to maintain 60 rpm despite vocal encouragement.

The participants reported to the laboratory in the morning on three other occasions (two resting trials and one submaximal cycle ergometry exercise trial, order randomly assigned) after a 12-h fast. However, upon arrival for the resting trials the subjects consumed 4.8 g of trans-10, cis-12 conjugated linoleic acid (CLA) or olive oil in capsule form as protocol for another study (16). For the exercise trial, the subjects consumed the olive oil capsules as protocol for the same study (16). The treatments were consumed immediately after the first resting measure in the resting trials and 80 min before the cycle ergometer exercise in the exercise trial. Upon arrival to the laboratory for all three trials, the SWA (equipment loaned by BodyMedia, Inc., Pittsburgh, PA) was placed on the subjects. The SWA provided by the manufacturer for this study was the exact device available to consumers. The subject's gender, age, height, and weight were programmed into the SWA before each trial. Initialization of the armband was completed using the InnerView™ Research Software, Version 1.0 (BodyMedia, Inc.).

TABLE 1. Descriptive characteristics of subjects, experiment 1.

Male (N = 13)	Value Mean (SD)	Range
Age (yr)	20.2 (1.0)	19–22
Weight (kg)	76.4 (11.1)	68–100
Height (cm)	176.4 (5.9)	170–185
Body fat (%)	14.4 (4.4)	7.0–22.4

TABLE 2. Descriptive characteristics of subjects, experiment 2.

	Value Mean (SD)	Range
Male (N = 10)		
Age (yr)	25.2 (3.2)	22–31
Weight (kg)	79.5 (17.2)	63–121
Height (cm)	180.9 (5.3)	175–188
Body fat (%)	10.8 (5.1)	4.2–18.6
Female (N = 10)		
Age (yr)	25.3 (3.2)	22–32
Weight (kg)	62.4 (10.1)	50–76
Height (cm)	163.8 (6.6)	155–175
Body fat (%)	18.6 (6.7)	7.9–29.3

For resting trials, four 10-min indirect calorimetry measurements were taken with the SensorMedics Vmax 29 using a plastic hood ventilation system over a 3-h period. There was an 80-min interval between the first and second measurement and then approximately 20 min between the 2nd, 3rd, and 4th measurements. During this time the subject reclined but remained awake.

For the exercise trial, the subject relaxed for roughly 90 min before any measurements were taken. The cycle ergometer protocol involved pedaling at 60 rpm at a fixed load, which represented 60% of each subject's predetermined $\dot{V}O_{2peak}$. Energy expenditure data was collected via a mouthpiece by the SensorMedics Vmax 229 system. This data was collected for minutes 1–10 (early), 19–23 (mid), and 31–40 (late) of the exercise bout. Upon completion of the exercise, the subject sat at rest on the cycle for 8 min while the energy expenditure of recovery was measured by the SWA and indirect calorimetry system.

Instrument calibration was performed before the first and second resting measurements in each of the resting trials and before the initial cycle ergometer exercise measurement in the exercise trial. The average $\dot{V}O_2$ and respiratory exchange ratio (RER) for each minute included in our analyses were used to compute a caloric value (kcal·min^{-1}) as described by McArdle et al. (12).

Experiment 2. Twenty healthy, nonsmoking adults (10 men, 10 women; Table 2) aged 18–35 yr were recruited to participate in this protocol. The subjects reported to the laboratory on only one occasion. They were instructed to refrain from consuming any food or performing any exercise for the 3 h before testing to ensure energy expenditure would not be elevated. Upon arrival to the laboratory, the subject's weight and height were measured. These data were programmed into the SWA along with the subject's age and gender using the InnerView™ Research Software (Version 1.0), and the SWA was placed on the subject.

The subject was connected to the SensorMedics Vmax 229 metabolic system via a mouthpiece, and continuous $\dot{V}O_2$ and RER measurements were collected for just over 40 min to determine energy expenditure. This time period included walking exercise on a treadmill for 30 min, the brief time to bring the treadmill to a stop, and a 10 min standing recovery. The exercise was divided into the following three levels of intensity for each 10 min period: 80.5 m·min^{-1} on a 0% grade, 107.3 m·min^{-1} on a 0% grade, and 107.3 m·min^{-1} on a 5% grade. After completing the final stage of exercise, the treadmill speed and incline were gradually decreased and the subject stood at rest for recovery measurement. The SWA and indirect calorimetry system collected data during this postexercise recovery period.

Data analysis. The internal clock in the SWA was synchronized daily with the clock used to record the indirect calorimetry measurements. The exact time (start and stop) of each indirect calorimetry measurement was recorded in order to synchronize with the SWA estimate. For analysis, rounding to the minute was done for the SWA reading but was kept within the same context and exercise intensity as the indirect calorimetry measurement; variation in measurements between the two devices was < 30 s. Due to the time it takes for an individual to reach a physiological steady-state condition and for the indirect calorimetry measurement to reflect actual energy expenditure, the first 5 min of each 10-min measurement and the first 2 min of the 5-min measurement were not used in our analysis. The analysis of the recovery from exercise utilized the entire 8- or 10-min measurement period because no physiological steady state was achieved.

The InnerView™ Research Software (Version 1.0, build 41) provided by BodyMedia, Inc. to analyze the SWA used a general energy expenditure model designed to provide a daily estimate; the software did not use specific contextual algorithms, such as biking or walking that would be needed to get the most accurate energy expenditure estimation for the specific time periods in this study. Therefore, each SWA data file (without the indirect calorimetry data) was sent to BodyMedia, Inc. along with a list of the contextual information (rest, bike, walk) and specific time frames for which energy expenditure data were needed. BodyMedia, Inc. conducted analyses on the experimental data files using their proprietary algorithms for specific contexts and returned the SWA energy expenditure estimations for each period.

Statistical analysis. Analysis of energy expenditure was performed with two-factor repeated measures ANOVA to test for effects of time, device, and time by device interaction in the cycle ergometer and rest protocols and similarly using intensity in place of time in the treadmill protocol. Paired *t*-tests were computed to examine differences between the measurements made by indirect calorimetry and the SWA for the average energy expenditure in the various contexts and total energy cost of the cycle ergometer bout. Pearson's product moment correlation analyses were performed to determine associations between the SWA estimate and indirect calorimetry measurement of energy expenditure for each of the measures assessed with the *t*-test and for the reliability of repeated measures of resting energy expenditure on different days by the SWA. Statistical significance was defined at $P < 0.05$. Data are presented as means ± SD. Bland-Altman bias plots were created to assess the agreement between the indirect calorimetry measurement and SWA estimation of energy expenditure as well as the reliability of the SWA estimate (1)—limits of agreement involve the mean difference between the two measurement tools ± 2 SD of the difference. Statistical analyses were completed using Statistical Packages for the Social Sciences software (SPSS, Version 11.0 for Windows, 2001, SPSS Inc., Chicago, IL) and Analyze-It™ General + Clinical Laboratory Statistics (Version 1.67, 2000, Analyze-It Software, Ltd., Leeds, UK).

RESULTS

Initially the data collected by the SWA was converted to energy expenditure using the software provided by the manufacturer, InnerView™ Research Software (Version 1.0). Resting energy expenditure with SWA and the commercial software provided was moderately lower (e.g., 1.1 vs 1.3 kcal·min^{-1} for the first resting measure) and cycling energy expenditure was substantially lower than that from indirect calorimetry (e.g., 4.9 vs 9.3 kcal·min^{-1} for the last period of the cycling bout). However, the energy expenditure estimate for treadmill at the three stages was higher than indirect calorimetry (e.g., 6.7, 8.6, and 9.0 kcal·min^{-1} compared with 3.7, 5.7, and 8.1 kcal·min^{-1} for each stage of treadmill with SWA and indirect calorimetry, respectively). As the manufacturer indicated the context detection was problematic (e.g., detection of when exercise began and stopped as well as specific activity) and specific contextual algorithms had not been used in those calculations, we sent the data files to the manufacturer for analysis with their specific contextual algorithms. The manufacturer was not provided with information on the specific workloads or any of the indirect calorimetry values.

Experiment 1: rest and ergometer protocols. As there was no significant effect of time on energy expenditure measured over four times during each rest trial, all of the four measures within a trial were averaged for analysis. The average energy expenditure value from the two resting trials did not differ (no effect of supplement ingested), so these values were averaged to result in one resting energy expenditure value per subject for each of the devices. The mean resting energy expenditure estimated by the SWA (1.3 ± 0.1 kcal·min^{-1}) did not differ from the mean indirect calorimetry measurement (1.3 ± 0.1 kcal·min^{-1}) ($P > 0.65$). The mean measurements for each subject provided by the two devices were significantly correlated ($r = 0.76$; $P < 0.004$). The Bland-Altman plot (Fig. 1) displays the good agreement between the two measures and no bias toward over- or underestimation. An approximation of the variation between the measures can be determined by dividing the average

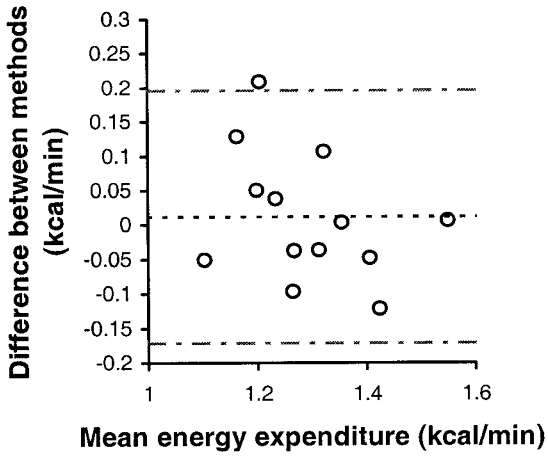

FIGURE 1—Bland-Altman bias plot between SWA estimate and IC measurement for average resting energy expenditure. The middle horizontal line represents the mean difference between the methods, and the other two lines represent the 95% limits of agreement. 95% Limits of Agreement = −0.17 to 0.20; 95% CI = −0.04 to 0.07; SWA, SenseWear™ Armband; IC, indirect calorimetry.

limit of agreement by the mean energy expenditure. For example, in Figure 1 the average limit of agreement is approximately 0.18 and the mean energy expenditure is approximately 1.3, so after dividing those numbers and then multiplying by 100, the approximate variation between the measures is 14%. The bias can be visualized by the spread of the points around the zero axis.

The SWA estimates from the two rest trials (from different days) were compared to assess the reliability of this device. This produced highly reliable estimates of energy expenditure at rest whether analyzed for each individual measure (range of r = 0.87–0.94) or the average of the four measures within a trial (r = 0.93; $P < 0.01$). The average mean energy expenditure of the measures was the same (1.3 kcal·min^{-1}) for both trials. Good agreement between the two trials was also found with the Bland-Altman bias plot (not shown) with limits of agreement ranging from −0.07 to 0.10 kcal·min^{-1}, which further emphasizes the high reliability of the resting energy expenditure estimate. Comparably, the reliability of the indirect calorimetry measured energy expenditure was lower for both the individual measures (range of r = 0.40–0.55) and the average of the four measures within each trial (r = 0.57; $P < 0.05$).

A significant time by device interaction occurred for the repeated measures ANOVA, used to analyze the 40-min cycle ergometer exercise, and was reflected by an increase in the SWA estimate of energy expenditure at each time period contrasted by the stable indirect calorimetry measurement. Although *post hoc* analysis did not show significant differences between the SWA estimate and indirect calorimetry measurement of energy expenditure for any time period assessed (Table 3), the greatest variation in means occurred early in exercise ($P > 0.07$). The SWA estimate poorly correlated with the measured energy expenditure early (r = 0.11; $P > 0.72$), mid (r = 0.12; $P > 0.70$), and late (r = 0.03; $P > 0.92$) in exercise. The Bland-Altman plots were similar for each time period assessed. Figure 2 represents the mid exercise time period and displays the wide limits of agreement between the two devices, with larger prediction errors seen for the individuals with the highest and lowest energy expenditures.

TABLE 3. Comparison of energy expenditure (kcal·min^{-1}) for constant intensity cycle ergometer exercise by IC and SWA.

Time Period	IC Mean (SD)	SWA Mean (SD)	IC vs SWA Difference (%)
Early	9.4 (1.5)	8.6 (0.5)	8.8
Mid	9.3 (1.4)	8.9 (0.5)	4.0
Late	9.2 (1.8)	9.1 (0.6)	1.3

Values are means of 3- (mid) or 5- (early and late) minute measurement periods. The devices were not significantly different during at any of the time points.
IC, indirect calorimetry; SWA, SenseWear™ Armband.

The indirect calorimetry energy expenditure measurement for the total cycle ergometer bout was calculated by multiplying the mean energy expenditure of the three measurement periods by the total duration of the exercise (40 min). The SWA collected data throughout the entire exercise session and generated a total energy expenditure estimate. Similar to the individual exercise time periods, the total energy expenditure over the exercise bout did not differ significantly ($P > 0.28$) between the SWA estimate (352.9 ± 20.3 kcal), but indirect calorimetry measurement (372.2 ± 60.4 kcal) and the two measures were poorly correlated (r = 0.11; $P > 0.73$).

The SWA estimated energy expenditure during the first 8 min of seated recovery from cycle exercise (25.3 ± 5.1 kcal) was significantly higher than the indirect calorimetry measured energy expenditure (18.5 ± 4.3 kcal) ($P < 0.003$), and the measures were poorly correlated (r = 0.09; $P > 0.77$).

Experiment 2: treadmill protocol. The SWA energy expenditure estimates for walking at three increasing intensities were significantly different from the energy expenditure measurements made by indirect calorimetry. The SWA significantly overestimated ($P < 0.02$) the energy expenditure of walking on a flat surface at both speeds (by 38% at

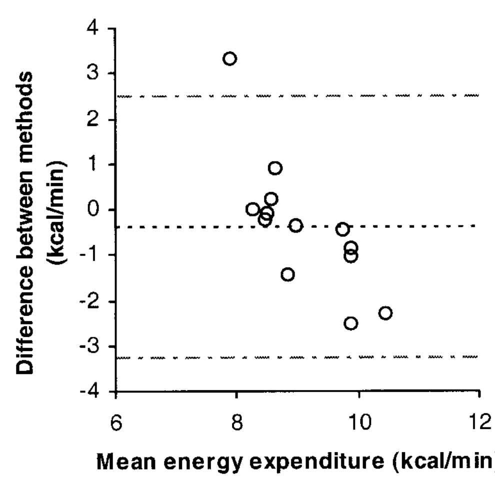

FIGURE 2—Bland-Altman bias plot between SWA estimate and IC measurement for mid (minutes 21–23) cycle ergometer exercise energy expenditure. The *middle horizontal line* represents the mean difference between the methods, and the *other two lines* represent the 95% limits of agreement; 95% limits of agreement = −3.26 to 2.52; 95% CI = −1.26 to 0.52; SWA, SenseWear™ Armband; IC, indirect calorimetry.

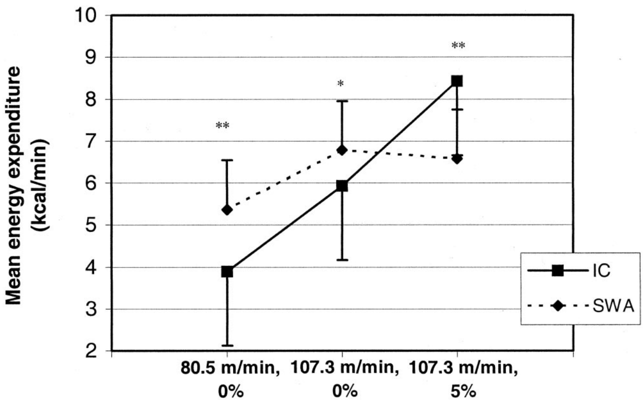

FIGURE 3—Mean walking exercise energy expenditure estimates of the SWA compared with measurements by IC. Values are means (± SD) of 5-min measurement periods; SWA, SenseWear™ Armband; IC, indirect calorimetry; * $P < 0.05$ for comparison of devices; ** $P < 0.01$ for comparison of devices.

80.5 m·min^{-1}, by 14% at 107.3 m·min^{-1}) and significantly underestimated ($P < 0.01$) the energy expenditure of walking on an inclination (by 22%) (Fig. 3). The correlation coefficients between the two energy expenditure assessments were highest for the lowest exercise intensity (r = 0.69; $P < 0.01$) and decreased with increasing exercise intensity (r = 0.54 for 107.3 m·min^{-1}, 0% grade, $P < 0.01$; r = 0.47 for 5% grade, $P < 0.04$). Bland-Altman plots (Fig. 4 and figures representing the other two exercise intensities (not shown)) emphasize the consistent over- and underestimation of the SWA energy expenditure estimate of walking on a flat surface and incline, respectively, and display the wide range of agreement. Figure 4 displays the bias plot for the lowest intensity, and although not shown, the limits of agreement for the 4 mph, 0% grade and 4 mph, 5% grade intensities were −1.90 to 3.62 kcal·min^{-1} and −6.21 to 2.52 kcal·min^{-1}, respectively. When separated by gender, the results of the analyses did not differ (data not shown).

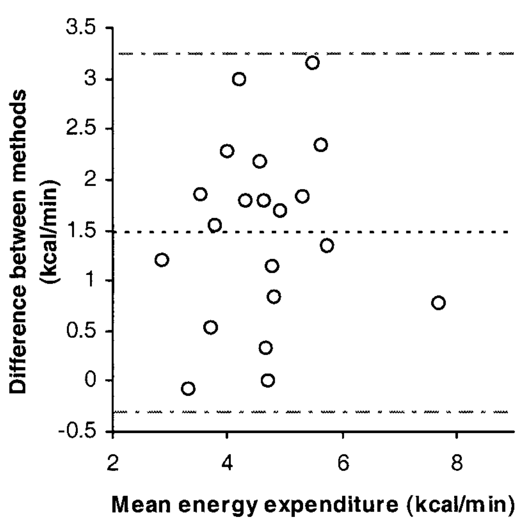

FIGURE 4—Bland-Altman bias plot between SWA estimate and IC measurement for 80.5 m·min^{-1}, 0% grade walking energy expenditure. The *middle horizontal line* represents the mean difference between the methods, and the *other two lines* represent the 95% limits of agreement; 95% limits of agreement = −0.29 to 3.25; 95% CI = 1.06 to 1.90; SWA, SenseWear™ Armband; IC, indirect calorimetry.

The energy expenditure immediately after the treadmill exercise was assessed for 10 min. The total energy expenditure estimate of recovery from exercise by the SWA (17.1 ± 4.9 kcal) did not differ significantly ($P > 0.11$) from the measured value (15.5 ± 7.8 kcal), and the two measures were highly correlated (r = 0.87; $P < 0.01$).

DISCUSSION

This study examined the validity and reliability of the SWA in estimating energy expenditure compared with simultaneous indirect calorimetry measurements in young, normal weight adults. The results indicate that the SWA can provide valid and reliable estimates of resting energy expenditure in this population. In addition, when compared with the triaxial accelerometer literature (2,9,11,13,19), the SWA appears to provide a better estimate of cycling exercise energy expenditure and a similar estimate of walking energy expenditure.

The resting energy expenditure estimates were valid based upon the fact that there were no significant differences between the energy expenditure measured via indirect calorimetry and estimated by the SWA, the measurements were highly correlated, and the measurements had good agreement. Chen and Sun (3) found accurate resting energy expenditure predictions by a triaxial accelerometer in their subjects living in a room calorimeter for 24 h; the accelerometer estimates did not differ from the measured values, and the two methods were highly correlated (r = 0.88). However, most accelerometer studies do not assess resting energy expenditure. The resting energy expenditure estimate made by triaxial accelerometers, based on subject age, gender, height, and weight (3,10), is only as accurate as the prediction equation used. The prediction model used to make the SWA resting energy expenditure estimate is proprietary, but the model uses both sensor data and characteristics of the wearer (age, height, weight). More research is needed to determine whether the incorporation of sensor data is more or less accurate in estimating resting energy expenditure than established prediction equations. Furthermore, it would be important to investigate if the SWA could detect and accurately estimate the slight elevation of energy expenditure over resting levels that occur with very light activities, as the majority of U.S. adults spend much of their time in primarily sedentary pursuits. Nichols et al. (13) found the triaxial accelerometer underestimated very light activity because it could not distinguish between sedentary states and very light activities.

In comparing the reliability of the energy expenditure measurement or estimation by indirect calorimetry and the SWA, respectively, the SWA demonstrated higher reliability. Although this may initially appear to favor the SWA over indirect calorimetry, it is possible that the SWA relies more on subject characteristics such as age, gender, and weight to calculate resting metabolic rate (RMR) and is not sensitive to small changes in energy expenditure from day to day. Elucidation of this issue would require further study. For example, RMR could be boosted by heating the body or taking medication to determine whether the SWA detected those changes.

Triaxial accelerometers have been shown to greatly underestimate the energy expenditure of nonweight-bearing activities (e.g., stationary cycling). Campbell et al. (2) found the triaxial accelerometer underestimated the mean ($\pm$ SD) cycling exercise energy expenditure by 2.8 $\pm$ 0.7 $kcal \cdot min^{-1}$, which equated to an underestimation of 53%. An even greater underestimation was found by Jakicic et al. (9) (mean of 4.7 $kcal \cdot min^{-1}$ or 68% underestimation). Compared with the literature on triaxial accelerometers, the SWA generated a more accurate estimate of cycle exercise energy expenditure; however, the SWA was not directly compared with an accelerometer. In this study, the SWA cycle ergometer exercise energy expenditure estimates did not differ significantly from the measurements made by indirect calorimetry. These findings demonstrate the promise of the SWA estimation capabilities; however, the poor correlation with the indirect calorimetry measurement ($r = 0.03$ to 0.12) and wide range of agreement (-3.8 to 3.5 $kcal \cdot min^{-1}$) in Bland-Altman analyses imply the SWA provides a close estimate of cycling exercise energy expenditure in groups but is unsuitable for an individual estimate. Without knowing the contribution of each sensor and subject characteristic in the SWA cycling exercise prediction model, it is difficult to speculate how the relationship between estimated and measured energy expenditure could be improved. The SWA detected the energy expenditure that occurred during cycle exercise at one intensity level; future research should assess whether the SWA can detect changes in cycle exercise intensity.

The SWA significantly overestimated the energy expenditure of walking on a horizontal surface (by 14–38%), detected the increase in speed, and underestimated the energy cost of walking on a 5% grade (by 22%) by not detecting the change in intensity that occurs with an increase in incline. These results are very comparable to those found in triaxial accelerometer studies (2,9,11,13,19). The energy expenditure of walking on a horizontal surface was significantly overestimated by triaxial accelerometers by 12–49% (2,13,19). The elevated energy expenditure that occurs when walking on an inclination was not detected by triaxial accelerometers (9,11)—underestimation ranged from 8 to 21% (9,13). The similar magnitude of over- and underestimation found in this study and triaxial accelerometer studies suggests the accelerometer in the SWA carries the most weight in the prediction model used to estimate ambulatory exercise energy expenditure. Improved energy expenditure estimates could potentially result from changing the ambulatory exercise model to provide more weight from other sensors (e.g., heat flux).

Most motion detectors are unable to measure the elevated energy expenditure immediately after exercise (15). It is recognized that there is potential error involved with the estimation of the recovery from exercise, as the subjects are not in physiological steady-state. However, with our measurements, the SWA was able to accurately estimate the energy expenditure in the period shortly after walking exercise but estimated 37% higher energy expenditure for the 8 min after cycle ergometry. In a study by Sherman et al. (15), the triaxial accelerometer significantly underestimated the energy expenditure associated with the recovery from treadmill exercise compared with an indirect calorimetry measurement. Only 34% of the postexercise energy expenditure was accounted for by the accelerometer. Thus, the SWA device was much better at estimating energy expenditure during recovery after exercise than that reported using an accelerometer alone.

The SWA was shown to be highly reliable at estimating the energy expenditure of rest. In this study the SWA resting energy expenditure estimates were the only valid estimates produced, compared with the indirect calorimetry energy expenditure measurements. It is necessary to test the reliability of the SWA in estimating the energy expenditure of other activities in various populations before conclusions can be made about the overall reliability of this device.

Our study had several limitations including the assumption that the indirect calorimetry measurements were stable and accurate. In addition, the ingestion of CLA or olive oil capsules in experiment 1 might be hypothesized to influence energy expenditure; however, Shute et al. (16) found no effect of CLA on $\dot{V}O_2$, RER, or energy expenditure in these subjects. Our results are only generalizable to healthy, young adults and to the few activities evaluated. More research is needed to evaluate the usefulness of this device with other populations such as overweight individuals and with a variety of activities. Although the SWA and indirect calorimetry measurements could not be synchronized exactly (always within 30 s), the use of at least 3-min intervals during steady-state activity would likely reduce any bias of this lack of perfect synchronization. Finally, a major limitation to the use of this device was the fact that contextual information on the exercise mode had to be supplied to the manufacturer so that the exercise-specific algorithms could be used. Context discrimination will be a critical requirement for any future versions of this software.

As little research has been published on this device, further research is warranted before firm conclusions on the reliability, validity, and utility of the SWA can be made. According to the manufacturer, the energy expenditure estimation models of the SWA and the software are being improved. The most recent analysis software (InnerView™ Research Software, Version 4.0) is reported to have improved ability to detect context but validation of this ability is mandatory in order to make the use of this device practical.

In summary, this study revealed that the SWA, using contextual algorithms from the manufacturer, provided a valid and reliable estimate of resting energy expenditure. Compared with the reports on triaxial accelerometers, the SWA generated improved energy expenditure estimates of cycling exercise and similar energy expenditure estimates of walking exercise when the correct contextual algorithm was used. The device was user-friendly in terms of easy attachment/detachment, minimal discomfort, and little or no interference in activity. More research is needed in more diverse populations and eventually with free-living activity before this device is ready for widespread use; however, it may have the potential to provide a feasible assessment of free-living energy expenditure.

BodyMedia, Inc., provided the SWA equipment and analyzed energy expenditure values from the armband data in support of this study.

Conflict of interest: The results of the present study do not constitute endorsement of the product by the authors or ACSM. No financial support for this study was obtained from BodyMedia, Inc.

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