Accuracy of Armband Monitors for Measuring Daily Energy Expenditure in Healthy Adults

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ABSTRACT

JOHANNSEN, D. L., M. A. CALABRO, J. STEWART, W. FRANKE, J. C. ROOD, and G. J. WELK. Accuracy of Armband Monitors for Measuring Daily Energy Expenditure in Healthy Adults. *Med. Sci. Sports Exerc.*, Vol. 42, No. 11, pp. 2134–2140, 2010. **Introduction**: There is a need to develop accurate devices for measuring daily energy expenditure under free-living conditions, particularly given our current obesity epidemic. **Purpose**: The purpose of the present study was to evaluate the validity of energy expenditure estimates from two portable armband devices, the SenseWear Pro3 Armband (SWA) monitor and the SenseWear Mini Armband (Mini) monitor, under free-living conditions. **Methods**: Participants in the study (30 healthy adults aged 24–60 yr) wore both monitors for 14 consecutive days, including while sleeping. Criterion values for total energy expenditure (TEE) were determined using doubly labeled water (DLW), the established criterion standard method for free-living energy expenditure assessment. **Results**: The average TEE estimates were within 112 $kcal\cdot d^{-1}$ for the SWA and within 22 $kcal\cdot d^{-1}$ for the Mini, but the absolute error rates (computed as the average absolute value of the individual errors) were similar for the two monitors (SWA = 8.1% ± 6.8%, Mini = 8.3% ± 6.5%). Using intraclass correlation (ICC) analysis, significant agreements were found between the SWA and DLW estimates of energy expenditure (ICC = 0.80, 95% CI = 0.89–0.70) and between the Mini and DLW (ICC = 0.85, 95% CI = 0.92–0.76). Graphical plots of the DLW TEE values against the difference between DLW and monitor estimates of TEE showed that the agreement was consistent across a range of TEE values. **Conclusions**: The SenseWear Pro3 and the SenseWear Mini armbands show promise for accurately measuring daily energy expenditure under free-living conditions. However, more work is needed to improve the ability of these monitors to accurately measure energy expenditure at higher levels of expenditure. **Key Words:** ACCELEROMETER, ACTIVITY MONITOR, ARMBAND, DOUBLY LABELED WATER, FREE-LIVING

The need for valid and reliable tools to accurately measure daily energy expenditure is an important public health research objective (23), particularly given the current epidemic of overweight and obesity. Numerous methods are available, but each has limitations; methods with good validity tend to be too costly or complicated for widespread use; however, practical and feasible methods for large populations are limited by poor accuracy and/or reliability. The doubly labeled water (DLW) method is the criterion standard for energy expenditure assessment under free-living conditions. The DLW method allows for the assessment of total energy expenditure (TEE) during 1–3 wk, and it has been shown to provide valid estimates of daily expenditure (27). The high cost and complicated analyses limit the use of DLW in most large epidemiological studies; however, the DLW technique provides a useful criterion measure for validating other instruments.

Accelerometers are the most practical and effective compromise between accuracy and feasibility for measuring energy expenditure. They provide objective information about physical activity, they are relatively inexpensive, and they are well tolerated by research participants. They have been widely used in research studies including use as a surveillance measure in the NHANES (24). Despite their wide acceptance in the research community, there are several limitations associated with the use of traditional accelerometry-based devices. There are currently many competing accelerometers, and there is considerable confusion over the appropriate interpretation of accelerometer counts and the conversion of these counts into estimates of physical activity or energy expenditure (14,25). Accelerometry-based activity monitors are also plagued by challenges associated with detecting and addressing compliance (12). Often, nonwear time cannot be distinguished from periods of inactivity, thereby necessitating detailed screening of data (2). Although this detailed screening is common practice now, there is still considerable confusion about what constitutes a full day of monitoring or what counts as inactivity. Progress has been made to resolve these issues, but it is likely

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Submitted for publication August 2009.
Accepted for publication March 2010.

0195-9131/10/4211-2134/0
MEDICINE & SCIENCE IN SPORTS & EXERCISE®

DOI: 10.1249/MSS.0b013e3181e0b3ff

that the fundamental challenges cannot be fully resolved without considerable enhancements in sensor and monitor technology.

Pattern recognition monitors that integrate information from multiple sensors and have a notion of "context" have recently emerged as a possible advance for activity monitoring. The SenseWear Pro3 Armband (SWA; BodyMedia, Inc., Pittsburgh, PA) is an example of such a pattern recognition device that addresses many of the limitations associated with single-axis accelerometers. The SWA monitor integrates information from a biaxial accelerometer and other physiological sensors (heat flux, temperature, and galvanic skin response sensors) to provide estimates of energy expenditure. The combination of sensors has shown to provide increased sensitivity for detecting the subtle changes in energy expenditure associated with complex lifestyle tasks and the increased energy expenditures associated with carrying loads, walking up grades, or doing nonambulatory activities (26). Previous studies have reported good validity of the SWA under laboratory conditions (4,6,7), but fewer studies have evaluated the device under free-living conditions. One recent free-living study (21) found reasonable agreement between the SWA (software V.4.02) and DLW for the measurement of TEE in healthy adults; however, significant differences in mean TEE between the two methods were found.

The proprietary algorithms for the SWA were recently modified, and the most current version of the software (V.6.1) has not been tested under free-living conditions. A smaller and thinner version of the SWA known as the SenseWear Mini (Mini) was also recently developed by the same company. The Mini is based on the same technology, but a three-axis accelerometer is used instead of the two-axis version in the SWA. The internal algorithms are slightly different between the monitors, so validation of this monitor is also needed. The purpose of the present study was to evaluate the validity of the SWA and the Mini for measuring TEE under free-living conditions by direct comparison with DLW.

METHODS

Participants

Thirty participants (15 men and 15 women) completed the study. The majority (73%) of the participants were white, 20% were Hispanic, and 7% were Asian. Approximately 27% of participants were overweight (body mass index (BMI) > 25 $kg \cdot m^{-2}$), and 10% of participants were characterized as obese (BMI > 30 $kg \cdot m^{-2}$). Participants were between the ages of 24 and 60 yr, did not have major disease or illness, did not use medications that would affect their body weight or metabolism, and were nonsmokers. Participants were recruited through word of mouth. Approval from the institutional review board of Iowa State University was obtained before beginning the study. Participants were aware of the procedures and purposes of the study before they signed the informed consent document.

Instruments

The SenseWear Pro3 (Model: 908901PROD2) is a wireless multisensor activity monitor that integrates motion data from a two-axis accelerometer along with several other physiological sensors (heat flux, skin temperature, and galvanic skin response). The monitor is worn on the upper arm over the triceps muscle and is lightweight (83 g) and comfortable to wear. Data were processed using the latest proprietary algorithms available in the software (software V.6.1, algorithm V.2.2.3). The SenseWear Mini (Model: MF-SW) is a newer and smaller version of the SWA. The Mini operates in a similar manner but includes a three-axis accelerometer rather than a two-axis accelerometer. Data were processed using similar algorithm architectures but with software specific for the Mini (software V.7.0, algorithm V.2.2.4).

The software calculates the energy expenditure for each minute of data using complex pattern recognition algorithms, composed of "activity classification" (context detection) and "energy expenditure estimation." A Naive Bays classifier is used to match the armband data to the activity class that best describes the current minute (the main classes are walking, running, stationary bike, road bike, rest, resistance, and other activity). Each activity class has a linear regression model, mapping the sensor values and body parameters to energy expenditure. Kilocalories and METs are converted using the following equation: METs = $kcal \cdot h^{-1} \cdot kg^{-1}$. The input to the Naive Bays classifier and the regression models include the data recorded in the armband and the SD of the data during several minutes before and after the minute in question.

Data Collection Procedures

Anthropometric data. Participants reported to the research center on the first day of the study (day 1) after a 10-h overnight fast (nothing to eat or drink except water). Anthropometric measurements were obtained in light clothing and in the absence of shoes. Body weight was measured to the nearest 0.1 kg using an electronic scale (Cardinal Detecto, Webb City, MO), and height was measured to the nearest 0.1 cm with a wall-mounted stadiometer (Ayrton, Prior Lake, MN). BMI was calculated as weight divided by height squared ($kg \cdot m^{-2}$).

Activity monitor data. The monitors were initialized using the participant's personal information (age, gender, height, and weight) and were adjusted to fit on the participant's arm. The SWA monitor was placed on the right arm, and the Mini monitor was placed on the left arm, according to manufacturer's recommendations. Participants were instructed to wear both monitors simultaneously from day 1 to day 14 (including while sleeping) but were allowed to remove the monitors briefly for showers or water activities. Participants were asked to keep a diary of nonwearing periods. Careful attention was given to processing the

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individual files to ensure that any gaps in the data did not influence the results. The brief gaps in the data attributable to showering were manually filled with a corresponding MET equivalent for "self-care activities" (2.0 METs) on the basis of the compendium of physical activities (1). The software detected other shorter gaps in the data, which occur if the strap is loosened or jostled during daily activities. The monitor beeps when this occurs, reminding the participant to tighten/adjust the strap, but small gaps still occurred. These gaps (ranging from 1 to 8 min in duration) were filled with the average energy expenditure of the 10 min before the defined gap. Planned gaps in the data occurred on day 7 for download and battery change/charge. This time was filled using MET estimates of light/resting because participants completed a sedentary activity during this time.

Several other longer periods of nonwear time (>30 min) were detected in the downloaded files. These gaps were filled with 2.0 METs, except in cases where participants reported doing water activities, for which corresponding MET values were applied using the compendium of physical activities (1). One participant removed the monitor while sleeping (547 min), so this gap was filled with estimates from sleeping on other nights. A large gap of more than 1529 min (>1 d) was also detected for one participant, and this occurred because of a battery malfunction. For this case, we used the corresponding values from the same day on the previous week to fill the data. The overall compliance with the monitoring protocol was excellent. The measured wear time (including all of the previously discussed potential gaps) averaged 1401 $\text{min}\cdot\text{d}^{-1}$ (97.1% ± 3.6%). The average nonwear time (approximately 39 min) was biased to some extent by the few participants who had larger gaps in the data. When the large gaps for the sleep and battery malfunction were excluded, the average nonwear time was 33 $\text{min}\cdot\text{d}^{-1}$.

DLW data. The DLW technique provided criterion measures of TEE. After the collection of two baseline (day 1) urine samples, participants were administered with 1.5-$\text{mL}\cdot\text{kg}^{-1}$ body weight of a mixture of 10% enriched $H_2{}^{18}O$ and 99% enriched ^2H_2O (Cambridge Isotopes, Cambridge, MA). The dose was followed by a 100-mL tap water rinse to ensure complete delivery of the labeled water. The first two urine samples after dosing (~1.5 and 3 h after dose) were discarded followed by two urine samples collected at 4.5 h and 6.0 h after dosing. On the mornings of days 7 and 14, participants were instructed to discard their first urine void and collect the second void of the day. Samples were collected in airtight containers and were brought to the research center in cooler packs. Abundance of ^{18}O was measured in duplicate on a Finnigan MAT 252 dual-inlet gas isotope ratio mass spectrometer (Finnigan MAT, Bremen, Germany), and $^2H_2$ abundance was measured in duplicate on the same isotope ratio mass spectrometer using a Finnigan H/D equilibration device. The ^2H and ^{18}O isotope elimination rates (k_D and k_O) were calculated using linear regression after a log transformation. Total body water (N) was determined at time 0, obtained from the regression line of the $H_2{}^{18}O$ isotope. The rate of CO_2 production was calculated using the equations of Schoeller (19) and was later modified (17) as follows:

$$r\text{CO}_2(\text{mol}\cdot\text{d}^{-1}) = (N/2.078)(1.007k_\text{O} - 1.041k_D) - 0.0246r_\text{GF},$$

where $r\text{CO}_2$ is the rate of carbon dioxide production; N is total body water calculated from $N_\text{O}/1.007$ where N_O is the ^{18}O dilution space; k_O and k_D represent the fractional elimination rates of ^{18}O and $^2H_2$, respectively; and r_GF is the rate of fractionated gaseous evaporative water loss, which is estimated to be $1.05N(1.007k_\text{O} - 1.041k_D)$. TEE was calculated as follows: TEE ($\text{kcal}\cdot\text{d}^{-1}$) = 22.4 $r\text{CO}_2$(3.9/RQ + 1.10). This formula assumes a respiratory quotient (RQ) of 0.86 that is typical for a healthy, rather low-fat diet. The corresponding energy equivalent of CO_2 (Eeq_{CO2}) was 5.637 $\text{kcal}\cdot\text{L}^{-1}$ CO_2. The DLW was processed and analyzed at the Pennington Biomedical Research Center. The intra-assay variability for DLW assessments is less than 2%.

To assess the ability of the monitors to measure energy expenditure associated with physical activity, we calculated daily physical activity energy expenditure (PAEE) using the following equation (18): PAEE = TEE − (resting metabolic rate + 0.1TEE). This approach uses the standard assumption that the thermic effect of food is approximately 10% of TEE (22). The resting metabolic rate (RMR) in this equation was estimated using standard World Health Organization equations (20) that are based on weight, age, and gender. The PAEE provides an indicator of total activity level, but we also calculated standardized estimates of usual physical activity level (PAL), calculated as TEE from DLW divided by estimated RMR.

Statistical Analyses

This study evaluated the agreement between estimates of TEE from the SWA and the Mini compared with the criterion estimates from the DLW. A secondary analysis included the comparison of PAEE estimates between the monitors and DLW. Primary statistical analyses were performed using JMP software v.7.0 (SAS Institute, Cary, NC). Paired *t*-tests were used to determine differences between the mean values obtained with the monitors and DLW. Simple linear regression analyses were conducted between armband and DLW energy expenditure estimates to evaluate the associations between measures. ANCOVA was used to test for the effects of gender on estimates of energy expenditure. No significant effects of gender were found; therefore, men and women were combined for all analyses. To evaluate the extent of agreement between measures of energy expenditure, intraclass correlations (ICC, one-factor random effect) were computed to determine agreement between measures (correlations closer to 1.0 indicate greater agreement) (3).

Graphical procedures were used to examine agreement across the range of TEE values (graphed using MATLAB v7.1; MathWorks, Natick, MA). The DLW estimate of TEE was plotted on the *x*-axis (rather than the mean of the DLW and monitor scores) because the DLW is a criterion measure.

TABLE 1. Participants' characteristics (mean ± SD and range (min–max)).

	Men (n = 15)	Women (n = 15)	All (n = 30)
Age (yr)	36.3 ± 9.7 (25–51)	40.1 ± 11.5 (24–60)	38.2 ± 10.6
Height (cm)	176 ± 6 (166–188)	167 ± 4 (162–175)	171 ± 7
Weight (kg)	78.5 ± 11.3 (66.1–107.7)	63.6 ± 11.6 (50.4–94.0)	71.2 ± 13.7
BMI (kg·m^{-2})	25.4 ± 3.0 (20.8–30.6)	22.7 ± 3.3 (17.8–31.5)	24.0 ± 3.4
PAL	1.7 ± 0.3 (1.2–2.4)	1.8 ± 0.2 (1.5–2.4)	1.73 ± 0.3

The differences between the DLW and monitor estimates were plotted on the y-axis to demonstrate the individual variability in responses. Confidence intervals defining the limits of agreement were established as 1.96 SD from the mean difference. To evaluate the presence of systematic bias, residuals of armband estimates of EE were plotted against the reference method DLW.

RESULTS

Physical characteristics for the 30 participants are presented in Table 1 along with descriptive PAL measures from the DLW measurements and RMR estimates. Table 2 contains the TEE and PAEE estimates from the monitors and differences from the DLW values. The SWA tended to underestimate TEE compared with the DLW method; however, the difference in TEE between the two methods was nonsignificant (P = 0.07). The TEE from the SWA was lower by an average of 112 kcal·d^{-1} compared with that from the DLW, representing an average of 4% underestimation in TEE. There was no significant difference in TEE estimates (P = 0.69) between the Mini and DLW. The TEE from the Mini was lower by an average of 22 kcal·d^{-1} compared with that from the DLW, an average underestimation of <0.1% in TEE. Estimates of TEE from the SWA and the Mini were not significantly different from each other (P = 0.5). Although the difference from DLW was smaller with the Mini, the error rates were similar (SWA = 8.1% ± 6.8%, Mini = 8.3% ± 6.5%) when expressed as absolute percentage error (computed using the absolute value of the differences). This suggests that the two monitors had similar absolute error compared with the DLW method. The regression analyses showed significant agreements between the SWA and DLW measurements of TEE (R^2 = 0.68, P < 0.001) and between the Mini and DLW measurements of TEE (R^2 = 0.71, P < 0.001; Fig. 1).

TABLE 2. Comparisons of TEE (mean ± SD).

	Mean ± SD	Mean Difference (Variable − DLW)	Range
TEE (kcal·d^{-1})			
DLW	2774 ± 576		2009–4144
SWA	2662 ± 483	−112 ± 325*	1798–3664
Mini	2752 ± 523	−22 ± 310	1764–3868
PAEE (kcal·d^{-1})			
DLW	983 ± 486		503–1515
SWA	769 ± 265	−123 ± 278**	242–1379
Mini	773 ± 283	−119 ± 286**	254–1575

* P = 0.07.
** Significantly different from DLW, P < 0.05.

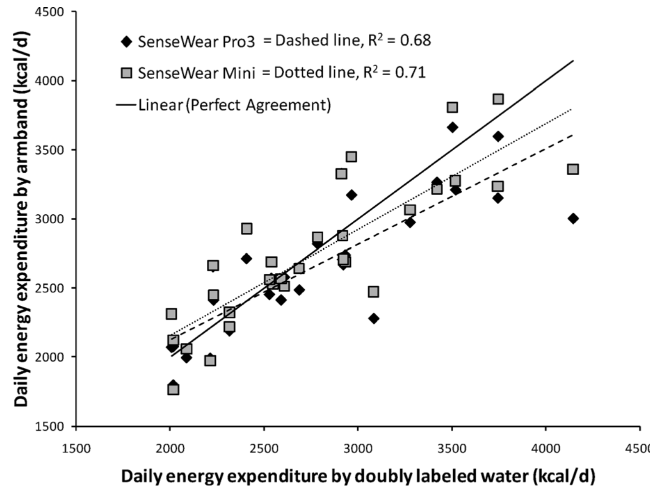

FIGURE 1—Regression analysis with Pearson correlation coefficients between the armbands and DLW methods for measuring daily energy expenditure (n = 30, P < 0.001 for both).

ICC were used to examine individual agreement in TEE values between the armband monitors and DLW. The ICC for the SWA and DLW was 0.80 (95% CI = 0.89–0.70), indicating that 80% of the variance in the measurements was explained by differences between individuals, whereas 20% was due to variation in the two methods. The ICC for the Mini and DLW was 0.85 (95% CI = 0.92–0.76), suggesting that 85% of the variation in TEE estimates was due to differences between individuals and 15% was due to variation between the Mini and DLW methods. For both monitors, the ICC exceeded the generally accepted threshold for good agreement of 0.75 (3).

The graphical plots in Figure 2 provide a more detailed view of the differences in measurement agreement between the monitors and the DLW method. The plots examine comparisons between the armbands and DLW by plotting differences in TEE between DLW and the armbands versus mean daily EE determined from DLW. Limits of agreement from the plots (mean ± 1.96 SD) were slightly smaller with the Mini monitor (−630 to 585 kcal·d^{-1}) than with the SWA monitor (−749 to 525 kcal·d^{-1}). Results of regressing the difference in TEE between each monitor and DLW (monitor TEE − DLW TEE) against DLW measures of TEE indicate that both monitors overestimated TEE at low levels of daily energy expenditure and significantly underestimated TEE at higher levels (SWA: R^2 = 0.30, P = 0.002, Mini: R^2 = 0.19, P = 0.02; Fig. 3). Overall, the SWA underestimated TEE in 19 (63%) of the 30 participants, and the Mini underestimated TEE in 17 (57%) of the 30 participants.

As a secondary analysis, we also examined the agreement between estimates of PAEE from the monitors compared with DLW. Both monitors significantly underestimated PAEE compared with DLW estimates (SWA: P = 0.02, Mini: P = 0.03; Table 2). The ICC for both monitors with DLW PAEE was 0.63 (95% CI = 0.77–0.47), indicating that 63%

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of the variance in the measurements was explained by differences between individuals and 37% was due to variation between the methods. Regression analyses revealed a modest agreement between SWA PAEE and DLW PAEE (R^2 = 0.51, P < 0.001) and a similar agreement between Mini PAEE and DLW PAEE (R^2 = 0.48, P < 0.001). Regressing the residual values of activity energy expenditure (monitor PAEE − DLW PAEE) on DLW PAEE revealed that both monitors significantly underestimated energy expenditure at higher levels of PAEE (SWA: R^2 = 0.56, P < 0.001, Mini PAEE: R^2 = 0.49, P < 0.001). Absolute errors of PAEE estimates were 26% for the SWA monitor and 28% for the Mini monitor, compared with DLW measures.

Because of the rather large ranges of age, BMI, and PAL across the participants, we conducted additional correlation analyses to determine whether the residuals from TEE and PAEE were related to these variables. We found no significant relationships between the TEE residuals and age or BMI; however, more negative residuals were associated with a higher PAL for both monitors (SWA: R^2 = 0.19, P = 0.02, Mini: R^2 = 0.18, P = 0.02), again suggesting that the monitors underestimate TEE at higher levels of energy expenditure. Residuals in PAEE were not associated with age, BMI, or PAL.

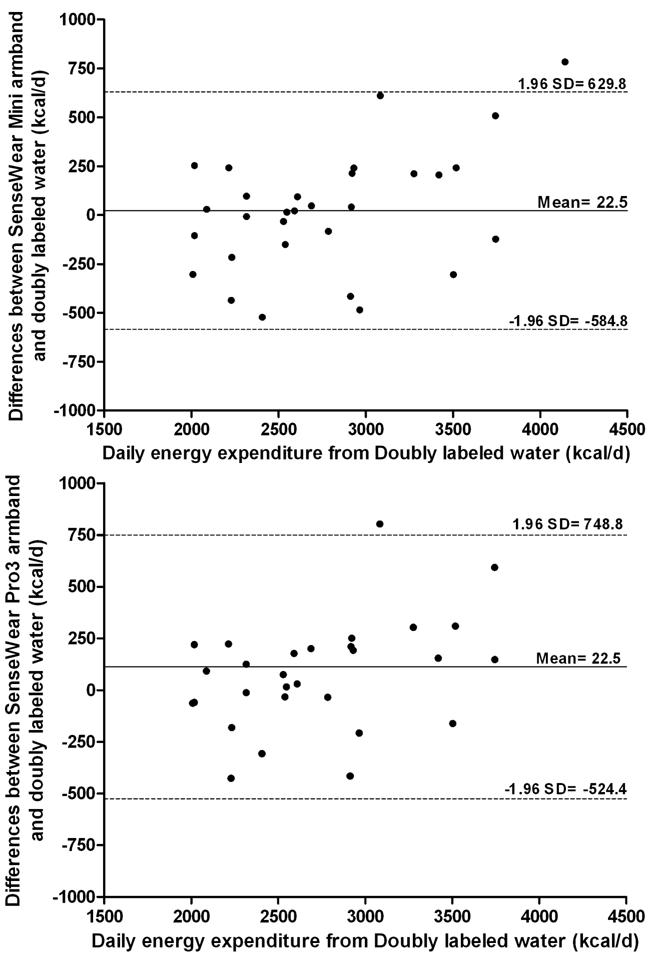

FIGURE 2—*Top panel*. Graphical plot between the Mini and DLW methods for measuring daily energy expenditure (n = 30). Estimates were averaged across 14 d to provide one estimate of energy expenditure. *Bottom panel*. Graphical plot between the SWA and DLW methods for measuring daily energy expenditure (n = 30). Estimates were averaged across 14 d to provide one estimate of energy expenditure.

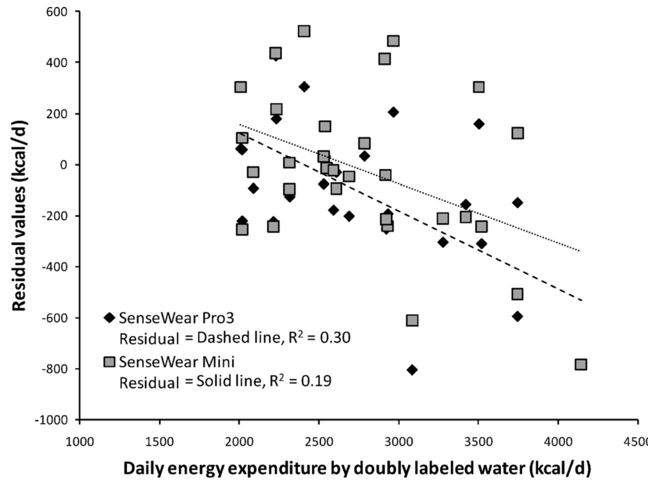

FIGURE 3—Residual values for daily energy expenditure (EE) plotted against the reference (DLW) method for measuring daily EE (n = 30). R^2 for the SWA regression is 0.30, P = 0.002, and R^2 for the Mini is 0.19, P = 0.02, indicating that both monitors significantly underestimate TEE at a higher DLW TEE.

DISCUSSION

We evaluated the accuracy of two armband monitors for measuring TEE and PAEE in healthy adults under free-living conditions compared with the criterion standard DLW. The development of accurate, reliable, and affordable tools to measure daily energy expenditure in free-living conditions is an important priority for public health researchers. The results of the present study support the use of these monitors for estimated daily energy expenditure, but the recently developed SenseWear Mini showed slightly better performance over the SenseWear Pro3, possibly because of the inclusion of a three-axis accelerometer (vs a two-axis accelerometer in SenseWear Pro3). For both monitors, examination of the graphical plots of the data and analyses of the residual versus DLW TEE values revealed greater underestimation of energy expenditure at higher TEE.

The results from the present study are generally consistent with findings from a previous study (21) that evaluated an earlier version of the SWA (software V.4.2). St-Onge et al. (21) reported that the SWA underestimated TEE by 117 kcal·d^{-1} (P < 0.01) compared with DLW during 10 d, whereas we found an underestimation of 112 kcal·d^{-1}. They reported similar values to ours for agreement between the SWA and DLW measures (ICC = 0.81) and association between the methods (R^2 = 0.74). Also consistent with our findings was the observation that the monitor underestimated TEE at higher levels of expenditure (R^2 = 0.33). Our study is the first to report data on the Mini monitor, which suggests some improvement in estimating TEE over the older SWA versions.

Several other studies have investigated the accuracy of activity monitors for measuring TEE compared with DLW, and these were highlighted in a recent review (16). The monitor most frequently studied is the ActiGraph (ActiGraph, Pensacola, FL), formerly known as the CSA (Computer Science Applications) and the MTI (Manufacturing Technology, Inc., Fort Walton Beach, FL). Validation studies of this monitor against DLW have involved primarily women, with additional studies in children and adolescents (16). Lof et al. (11) compared TEE measured by the CSA with DLW in 34 women and found a nonsignificant difference of 88 kcal·d^{-1}; however, the limits of agreement were large (±700 kcal·d^{-1}). Another study by this group (10) again compared the CSA with DLW in 24 healthy women and found a mean difference in TEE of 6 ± 325 kcal·d^{-1}, with no systematic bias present. Masse et al. (13) compared the CSA monitor with DLW in a group of 136 African-American and Hispanic women. The monitor was worn during the last 7 d of the 14-d DLW period. A modest agreement was found between the monitor and DLW estimates of TEE, R^2 ranging from 0.39 to 0.44, depending on whether controlling for body mass or fat-free mass. Leenders et al. (9) compared TEE measured by the CSA and Tri Trac monitors with DLW and found modest associations (R^2 ranging from 0.17 to 0.45); however, concordance between the monitors and DLW ranged from 0.04 to 0.50, considered slight to moderate (8). Both monitors provided reasonable estimates of TEE, with some underestimation (−2% to −23%); however, SD were large.

A study by Hustvedt et al. (5) evaluated the accuracy of the ActiReg (a three-dimensional accelerometer) alone and in combination with a HR monitor. Mean TEE measured by the ActiReg was not different from DLW (P = 0.45), with a mean difference of 98 kcal·d^{-1} and limits of agreement of −397 to 765 kcal·d^{-1}. Bland–Altman plots showed that the ActiReg underestimated TEE at higher levels of energy expenditure, which was reduced by using the HR function. Plasqui et al. (15) evaluated another three-dimensional monitor called the Tracmor. They reported that participant characteristics such as age, body mass, and height explained 64% of the variation in DLW TEE, but adding Tracmor activity counts to the model increased the explained variation by 19% (total R^2 = 0.83). In our study, we found that age, body mass, and height explained 40% of the variation in DLW TEE. Adding SWA TEE to the model increased the explained variation by 29% (total R^2 = 0.69, P < 0.001), indicating that the movement and other physiological sensors provide useful information to improve estimates of TEE. Similar results were obtained when the analyses were repeated with the Mini, with the explained variance increasing by 32% (R^2 = 0.72, P < 0.001). Adding both monitors to the model did not explain further variance, indicating that the monitors function independently, and there is no additive benefit of using multiple monitors.

We found poorer performance of the monitors for measuring PAEE. Both monitors significantly underestimated PAEE (particularly at higher levels of activity expenditure) and may have contributed to the overall underestimation of TEE. St-Onge et al. (21) reported an average underestimation in PAEE of 225 kcal·d^{-1}, whereas we observed an underestimation of 123 and 119 kcal·d^{-1} (for SWA and Mini, respectively), suggesting some improvement. We also found better agreement between the monitors and DLW (ICC = 0.63) than that in the study of St-Onge et al. (ICC = 0.46) despite similar associations between the methods (R^2 = 0.48 and R^2 = 0.51 vs St-Onge R^2 = 0.49). It is important to note, however, that caution should be exercised when interpreting the results of our PAEE data because RMR was not measured with an indirect calorimeter but instead was estimated using World Health Organization equations (20).

The results of the present study show that the SenseWear Pro3 and the SenseWear Mini perform similar to or better than other available monitors. Both monitors underestimated energy expenditure, particularly at higher levels of expenditure, and this underestimation continues to be a problem among many activity monitors that are currently available. The tendency for underestimation can be attributed to the inherent challenges of capturing low-intensity activities of daily living, which contribute to TEE but are difficult to detect with accelerometer technology. An advantage of the multisensor armband technology is the inclusion of thermal and perspiration-related sensors as well as accelerometers. The heat sensors provide a way to detect the subtle increases in energy expenditure associated with low-intensity activities. Previous research with the armband has indicated that the SWA provides more accurate estimates of low-intensity activities than the ActiGraph (26). This may have contributed to the improved performance relative to previous DLW studies with the ActiGraph. Another possible reason for the improved result is the better detection (and correction) of nonwear time. This capability removes the guesswork that is often needed to address gaps in the data, which occur with other monitors, allowing for more confidence in the results (i.e., underestimation or overestimation by the monitors is due to capability of the monitor and not to error introduced by using assumed energy expenditure data).

Our study is not without limitations. Most volunteers who participated were quite lean and active, likely more so than an average population. There is also the possibility of "reactivity" when wearing the monitors, that is, subjects may have increased their daily activity over their usual patterns while wearing the monitor. However, our subjects were instructed to maintain their usual daily routines of work, activity, etc., while wearing the monitors. Also, limitations of the monitors themselves include the proprietary nature of the algorithms, which do not allow for independent investigators to work with the algorithms, and the cost of the monitor, which is less than some available but is likely not a negligible expense.

In summary, the SenseWear Pro3 and the SenseWear Mini armbands show promise for accurately measuring daily energy expenditure under free-living conditions. An advantage of these monitors is that they provide direct estimates of wear time and avoid challenges associated with evaluating compliance. The monitors also provide direct estimates of energy expenditure and avoid the confusion in the literature caused by the availability of different calibration equations for different populations. However, more work is needed to improve the ability of these monitors to accurately measure energy expenditure at higher levels of expenditure.

This research was funded by a grant from Bodymedia, Inc., awarded to Dr. Greg Welk.

The results of the present study do not constitute endorsement by the American College of Sports Medicine.

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