Evaluation of the SenseWear Pro Armband™ to Assess Energy Expenditure during Exercise

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ABSTRACT

JAKICIC, J. M., M. MARCUS, K. I. GALLAGHER, C. RANDALL, E. THOMAS, F. L. GOSS, and R. J. ROBERTSON. Evaluation of the SenseWear Pro Armband™ to Assess Energy Expenditure during Exercise. *Med. Sci. Sports Exerc.*, Vol. 36, No. 5, pp. 897–904, 2004. **Purpose:** To assess the accuracy of the SenseWear Pro Armband™ for estimating energy expenditure during exercise. **Methods:** Forty subjects (age = 23.2 ± 3.8 yr; body mass index = 23.8 ± 3.1 kg·m^{-2}) performed four exercises (walking, cycling, stepping, arm ergometry) with each exercise lasting 20–30 min and workload increasing at 10-min intervals. Subjects wore the SenseWear Pro Armband™ on the right arm, and energy expenditure was estimated using proprietary equations developed by the manufacturer. Estimated energy expenditure from the SenseWear Pro Armband™ was compared with energy expenditure determined from indirect open-circuit calorimetry, which served as the criterion measure. **Results:** When a generalized proprietary algorithm was applied to the data, the SenseWear Pro Armband™ significantly underestimated total energy expenditure by 14.9 ± 17.5 kcal (6.9 ± 8.5%) during walking exercise, 32.4 ± 18.8 kcal (28.9 ± 13.5%) during cycle ergometry, 28.2 ± 20.3 kcal (17.7 ± 11.8%) during stepping exercise, and overestimated total energy expenditure by 21.7 ± 8.7 kcal (29.3 ± 13.8%) during arm ergometer exercise ($P \leq 0.001$). At the request of the investigators, exercise-specific algorithms were developed by the manufacturer and applied to the data that resulted in nonsignificant differences in total energy expenditure between indirect calorimetry and the SenseWear Pro Armband™ of 4.6 ± 18.1 kcal (2.8 ± 9.4%), 0.3 ± 11.3 kcal (0.9 ± 10.7%), 2.5 ± 18.3 kcal (0.9 ± 11.9%), and 3.2 ± 8.1 kcal (3.8 ± 9.9%) for the walk, cycle ergometer, step, and arm ergometer exercises, respectively. **Conclusions:** It appears that it is necessary to apply exercise-specific algorithms to the SenseWear Pro Armband™ to enhance the accuracy of estimating energy expenditure during periods of exercise. When exercise-specific algorithms are used, the SenseWear Pro Armband™ provides an accurate estimate of energy expenditure when compared to indirect calorimetry during exercise periods examined in this study. **Key Words:** INDIRECT CALORIMETRY, CALORIC EXPENDITURE, PHYSICAL ACTIVITY, HEAT FLUX

Physical activity is associated with reduced morbidity and mortality for many chronic diseases including cardiovascular disease, diabetes mellitus, and some forms of cancer (13). Physical activity has also been shown to improve weight loss when combined with modifications in eating behaviors (7) and is one of the best predictors of long-term weight loss maintenance (9,11). Despite these benefits, a significant number of adults in the United States do not participate in sufficient amounts of physical activity to elicit health benefits (4).

One of the challenges facing physical activity researchers and clinicians is the ability to accurately assess physical activity in free-living individuals. Each of the current methods of assessing physical activity and energy expenditure in free-living individuals has limitations. Doubly labeled water is considered one of the most accurate techniques of assessing energy expenditure in free-living individuals (12). However, doubly labeled water is expensive and provides information regarding the average energy expenditure over a 7- to 14-d period rather than specific information related to the pattern of physical activity across each 24-h period. Accelerometers have been used to assess physical activity and energy expenditure in free-living individuals. Although they can typically differentiate between active and inactive individuals (5,6), they are most accurate during periods of level walking and jogging (8). Pedometers can be used to assess the number of steps taken; however, there may be error when steps are converted to energy expenditure (14). Moreover, distance measured may vary based on the type of pedometer used and the locomotor speed (3). Physical activity questionnaires rely on self-report, which may limit the accuracy of this technique compared with other more objective techniques (5). Therefore, there continues to be a

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need to develop objective techniques to assess energy expenditure associated with physical activity in free-living individuals.

The SenseWear Pro Armband™ (Body Media, Pittsburgh, PA) is a newly developed commercially available device to assess energy expenditure. This device is worn on the right upper arm over the triceps muscle and monitors various physiological and movement parameters. Data from a variety of parameters including heat flux, accelerometer, galvanic skin response, skin temperature, near-body temperature, and demographic characteristics including gender, age, height, and weight are used to estimate energy expenditure utilizing proprietary equations developed by the manufacturer. Compared with other commercially available portable devices to estimate energy expenditure, the inclusion of a heat flux sensor is the new technology incorporated into the SenseWear Pro Armband™. Heat production and heat loss is a by-product of metabolism and energy expenditure, and therefore the ability to measure this parameter may improve the estimate of energy expenditure when used in combination with other parameters such as accelerometry. However, the validity of the SenseWear Pro Armband™ to estimate energy expenditure awaits independent evaluation across a variety of activities. Therefore, the purpose of this study was to examine the validity of the commercially available SenseWear Pro Armband™ to assess energy expenditure during four different modes of exercise.

METHODS

Subjects

Forty subjects were recruited from students and staff at the University of Pittsburgh to participate in this study. Participants included 20 men and 20 women. Eligible subjects were 18–35 yr of age (mean ± SD = 23.2 ± 3.8 yr) and had a body mass index between 20 and 30 $kg \cdot m^{-2}$ (mean ± SD = 23.8 ± 3.1 $kg \cdot m^{-2}$). All subjects completed a physical activity readiness questionnaire (PAR-Q) and medical history before participation in this study. Subjects with a medical condition that could prevent safe participation in moderate to vigorous intensity exercise, or with a medical condition that would require medical clearance before participation, were excluded from this study. Research procedures were approved by the Institutional Review Board at the University of Pittsburgh, with written informed consent obtained before subjects participating in this study. Subjects were compensated $50 upon completion of this study.

Experimental Methods

Measurement of descriptive variables. Weight was measured to the nearest 0.25 lb (0.1 kg) on a balance-beam scale before the exercise sessions with the subject in light-weight clothing (shorts and T-shirt and no shoes). Height was measured to the nearest 0.25 inch (0.64 cm) using a stadiometer with the subject not wearing shoes. Body mass index (BMI = $kg \cdot m^{-2}$) was computed from weight and height.

Exercise Protocols

Subjects participated in four separate exercise protocols that included treadmill walking, stair stepping, cycle ergometry, and arm ergometry. The specific protocols are shown in Table 1. The order in which the different exercise protocols were performed was randomly assigned. Walking was performed on a motorized treadmill. Stair stepping was performed on an 8-inch (20.3 cm) bench with each step cycle performed in the following sequence: step up with dominant leg, step up with nondominant leg, step down with dominant leg, and step down with nondominant leg. Cycle ergometer exercise was performed on a Monarch 818E, with arm ergometry performed using a Monarch Rehab Trainer arm ergometer. The pace during stair stepping, cycle ergometry, and arm ergometry was regulated using a metronome.

During each exercise protocol, energy expenditure was measured simultaneously using open-circuit calorimetry (criterion method) and the SenseWear Pro Armband™ (comparison method). Exercise heart rate was used to assess exercise intensity at each minute using a Polar Vantage NV heart rate monitor.

Open-circuit calorimetry. The criterion method of assessing energy expenditure during each exercise protocol was open-circuit calorimetry. A Parvomedics (Sandy, UT) or a SensorMedics Vmax (Yorba Linda, CA) metabolic cart was used to measure minute-by-minute oxygen uptake and the respiratory exchange ratio (RER). The Parvomedics metabolic cart was only available during the testing of approximately 50% of the subjects due to scheduling conflicts, and therefore the remaining subjects were tested using the SensorMedics metabolic cart. Energy expenditure ($kcal \cdot min^{-1}$) was computed by multiplying the oxygen uptake ($L \cdot min^{-1}$) by the caloric equivalent based on the RER. There was no difference in the results of this study based on which of these metabolic carts was used for data collection, and therefore data were combined for analysis.

SenseWear Pro Armband™. Information provided by the manufacturer (See www.bodymedia.com) indicates that the SenseWear Pro Armband™ incorporates a variety

TABLE 1. Description of exercise protocols.

Exercise Mode	Workload	Time (min)	Speed ($m \cdot min^{-1}$)	Grade (%)
Treadmill walking	1	1–10	80.4	0
	2	11–20	80.4	5
	3	21–30	80.4	10
			Step cycles (step cycles·min^{-1})	Step height (cm)
Stair stepping	1	1–10	20	20.32
	2	11–20	35	20.32
			Speed (rpm)	Resistance (kg)
Cycle ergometer	1	1–10	50	0.5
	2	11–20	50	1.5
			Speed (rpm)	Resistance (kg)
Arm ergometer	1	1–10	50	1.0
	2	11–20	75	1.0

of measured parameters (accelerometry, heat flux, galvanic skin response, skin temperature, near-body temperature) and demographic characteristics (gender, age, height, weight) into proprietary algorithms to estimate energy expenditure. Accelerometry is measured using a two-axis micro-electronic-mechanical sensor. Heat flux is measured using a proprietary sensor that incorporates low thermal resistant materials and thermocouple arrays. Galvanic skin response is used as an indicator of evaporative heat loss and is measured using two hypoallergenic stainless steel electrodes. Skin temperature is used to reflect the body's core temperature activity and is measured using a thermistor-based sensor. Near-body temperature sensor measures the temperature of the cover on the side of the armband.

As recommended by the manufacturer, the SenseWear Pro Armband™ (version 3.0) was worn on the right arm over the triceps muscle at the midpoint between the acromion and olecranon processes. Upon entering the laboratory, the armband was placed on the subject's arm and worn while in a seated position for a period of 15 min before data collection to allow for acclimation to skin temperature. Energy expenditure during exercise was computed at 1-min intervals. Energy expenditure during each of the exercises included in this study was estimated using a generalized proprietary algorithm (Innerview Research Software Version 3.2) developed by the manufacturer.

At the request of the investigators, the manufacturer also agreed to develop exercise-specific algorithms to assess whether these would improve the estimation of energy expenditure using the SenseWear Pro Armband™. The manufacturer selected the walking trials from their existing database to develop a treadmill walking equation that was applied to the data collected in this current study. However, before this study, the manufacturer reported having limited data available from which they could develop an exercise-specific equation for cycle ergometer, step, or arm ergometer exercise. Therefore, data from 16 subjects for cycle exercise, 18 subjects for step exercise, and 18 subjects for arm ergometry exercise were randomly selected from this current study, and these data were provided to the manufacturer for the development of exercise-specific proprietary equations. These newly developed exercise-specific proprietary equations were applied to the data from the remaining subjects to compute energy expenditure for each of these exercises before data analysis.

Statistical Analysis

Statistical analysis was performed using SPSS (version 11.0). Data were analyzed separately for each exercise protocol. Statistical significance was defined with an alpha level of $\leq$0.05, with the critical alpha level adjusted using the Bonferroni procedure for multiple comparisons within each mode of exercise (*P* value for two comparisons $\leq$ 0.025; *P* value for three comparisons $\leq$ 0.016). Intraclass correlation coefficients were calculated for comparison between the armband and indirect calorimetry. Two-factor repeated measures ANOVA was performed to assess differences in the measurement techniques (indirect calorimetry vs SenseWear Pro Armband™) across changes in workload. Both measurement technique and workload were considered as within-subject variables in the repeated measures ANOVA. Total energy expenditure summed across each exercise protocol was analyzed with dependent *t*-tests to compare indirect calorimetry and the SenseWear Pro Armband™. Moreover, data were analyzed using the procedure described by Altman and Bland (1) to assess the differences between energy expenditure measured using indirect calorimetry and estimated using the SenseWear Pro Armband™.

RESULTS

Of the 40 subjects who participated in this study, complete data were available for 31 subjects for treadmill walking exercise, 34 subjects for cycle exercise, 36 subjects for stepping exercise, and 35 subjects for arm exercise. The missing data resulted from either failure of the SenseWear Pro Armband™ to provide complete data (walking = 9,

TABLE 2. Demographic characteristics of subjects.

Exercise Mode	Variable	Trials Using Body Media's Generalized Algorithm	Trials Using Exercise-Specific Algorithms: Subjects to Develop New Algorithm	Subjects to Test Algorithm	Difference (Mean ± SE)
Treadmill walking		*N* = 31		*N* = 31	
	Age (yr)	23.3 ± 3.7		23.3 ± 3.7	
	Weight (kg)	69.6 ± 13.3		69.6 ± 13.3	
	Body mass index (kg·m^{-2})	24.0 ± 3.1		24.0 ± 3.1	
Cycle ergometer		*N* = 34	*N* = 16	*N* = 18	
	Age (yr)	23.1 ± 3.5	21.8 ± 2.5	24.3 ± 3.9	2.5 ± 1.1*
	Weight (kg)	68.4 ± 12.9	70.9 ± 11.8	66.2 ± 13.8	4.8 ± 4.4
	Body mass index (kg·m^{-2})	23.7 ± 3.0	24.1 ± 2.7	24.3 ± 3.2	0.8 ± 1.0
Stair stepping		*N* = 36	*N* = 18	*N* = 18	
	Age (yr)	23.1 ± 3.7	22.2 ± 2.9	24.0 ± 4.2	1.8 ± 1.2
	Weight (kg)	70.5 ± 13.4	71.9 ± 11.4	69.0 ± 15.4	2.8 ± 4.5
	Body mass index (kg·m^{-2})	24.0 ± 3.2	24.4 ± 2.8	23.6 ± 3.5	0.8 ± 1.1
Arm ergometer		*N* = 35	*N* = 18	*N* = 17	
	Age (yr)	22.9 ± 3.5	22.2 ± 2.9	23.7 ± 4.0	1.5 ± 1.2
	Weight (kg)	70.2 ± 14.1	71.9 ± 11.4	68.5 ± 16.6	3.4 ± 4.8
	Body mass index (kg·m^{-2})	24.0 ± 3.3	24.4 ± 2.8	23.6 ± 3.8	0.8 ± 1.1

* Indicates that mean difference statistically significant at $P \leq 0.05$.

TABLE 3. Heart rate response during exercise.

Exercise Mode	Exercise Interval	Trials Using Body Media's Generalized Algorithm		Trials Using Exercise-Specific Algorithms: Subjects to Develop New Algorithm		Trials Using Exercise-Specific Algorithms: Subjects to Test New Algorithm		Trials Using Exercise-Specific Algorithms: Difference (Mean ± SE)	
		HR (bpm)	% HRmax	HR (bpm)	% HRmax	HR (bpm)	% HRmax	HR (bpm)	% HRmax
Treadmill walking		*N* = 31				*N* = 31			
	1–10 min	99.7 ± 19.4	50.7 ± 9.8			99.7 ± 19.4	50.7 ± 9.8		
	11–20 min	112.0 ± 15.0	57.0 ± 7.7			112.0 ± 15.0	57.0 ± 7.7		
	21–30 min	133.0 ± 19.7	67.7 ± 10.1			133.0 ± 19.7	67.7 ± 10.1		
Cycle ergometer		*N* = 34		*N* = 16		*N* = 18			
	1–10 min	96.8 ± 12.4	49.2 ± 6.5	93.9 ± 13.2	47.4 ± 6.7	99.4 ± 11.5	50.8 ± 6.0	5.5 ± 4.2	3.4 ± 2.2
	11–20 min	128.2 ± 26.5	65.2 ± 13.5	120.8 ± 14.4	61.0 ± 7.5	134.8 ± 32.9	68.9 ± 16.6	14.0 ± 8.9	7.9 ± 4.5
Stair stepping		*N* = 36		*N* = 18		*N* = 18			
	1–10 min	108.4 ± 13.1	55.0 ± 6.6	107.6 ± 13.2	54.4 ± 6.9	109.3 ± 13.3	55.7 ± 6.5	1.7 ± 4.5	1.2 ± 2.3
	11–20 min	144.2 ± 18.5	73.2 ± 9.4	141.7 ± 17.3	71.6 ± 9.0	146.9 ± 19.9	74.8 ± 9.7	5.2 ± 6.3	3.1 ± 3.2
Arm ergometer		*N* = 35		*N* = 18		*N* = 17			
	1–10 min	93.4 ± 14.1	47.4 ± 7.5	88.5 ± 14.1	44.8 ± 7.5	98.6 ± 12.6	50.2 ± 6.5	10.1 ± 4.5*	5.5 ± 2.4*
	11–20 min	114.1 ± 20.0	57.9 ± 10.5	107.1 ± 16.5	54.2 ± 8.9	121.5 ± 21.1	61.9 ± 10.9	14.3 ± 6.4*	7.7 ± 3.4*

* Indicates that mean difference statistically significant at $P \leq 0.05$.

cycle ergometer = 5, stepping = 4, arm ergometer = 5) or the unwillingness of the subject to complete the exercise session (cycle ergometer = 1). Descriptive characteristics of subjects are shown in Table 2. Because new proprietary equations were developed from the data collected as part of this study for the cycle, step, and arm exercises, independent *t*-tests were performed to examine differences between subjects used to develop the proprietary equations and subjects on which these proprietary equations were applied (see Table 2).

Heart rate data for each of the exercise protocols are presented in Table 3. The percent of age-predicted maximal heart rate (%HRmax) was computed for each workload for each of the exercise protocols. The mean %HRmax was approximately 50% of HRmax for the lowest workloads and approximately 70% of HRmax at the highest workloads across each of the exercise protocols. These data reflect light to moderate exercise intensity based on existing intensity classifications (2).

Intraclass correlation coefficients were computed between total energy expenditure from indirect calorimetry and the SenseWear Pro Armband™ for each of the four exercises examined in this study. When the generalized equation to estimate total energy expenditure using the SenseWear Pro Armband™ was applied to the data, intraclass correlations were 0.77 (CI: 0.57–0.88), 0.28 (CI: −0.05–0.56), 0.63 (CI: 0.39–0.79), 0.74 (CI: 0.55–0.86) for walking, cycle ergometry, step, and arm ergometry exercise, respectively. By comparison, the intraclass correlations when the exercise-specific equations were applied to the data to estimate total energy expenditure using the SenseWear Pro Armband™ were 0.87 (CI: 0.75–0.93) for treadmill walking, 0.89 (CI: 0.74–0.95) for cycle ergometer, 0.82 (CI: 0.58–0.92) for stepping, and 0.66 (CI: 0.28–0.86) for arm ergometer exercise. Intraclass correlation coefficients between energy expenditure from indirect calorimetry and the SenseWear Pro Armband™ were also computed for each 10-min workload during each of the exercise protocols. Data for each 10-min workload using the generalized equation to estimate energy expenditure are presented in Table 4, whereas data using the exercise-specific equations to estimate energy expenditure are presented in Table 5.

The results from the two-factor (method × workload) repeated measures ANOVA for each of the exercise protocols using the commercially available generalized algorithm for the SenseWear Pro Armband™ to estimate energy expenditure are presented in Table 4. Significant method × workload interactions were shown for all the modes of exercise ($P < 0.001$). *Post hoc* analyses were performed to compare the energy expenditure during each 10-min workload between indirect calorimetry and the SenseWear Pro Armband™, with the critical *P* value adjusted based on the number of comparisons within each exercise mode using the Bonferroni procedure. Results of the posthoc analyses showed that during walking exercise the SenseWear Pro Armband™ significantly overestimated energy expenditure during minutes 1–10 by 1.3 ± 0.5 kcal·min^{-1}, and signif-

TABLE 4. Comparison of energy expenditure between indirect calorimetry and SenseWear Pro Armband™ using commercially available generalized algorithm (mean ± SD).

Exercise Mode	Exercise Minutes	Energy Expenditure (kcal·min^{-1}): Measured (Indirect Calorimetry)	Energy Expenditure (kcal·min^{-1}): Estimated (Armband)	Intraclass Correlation: Correlation	Intraclass Correlation: 95% CI	*P* for Repeated Measures ANOVA: Method	*P* for Repeated Measures ANOVA: Workload	*P* for Repeated Measures ANOVA: Method × Workload
Treadmill walking (*N* = 31)	1–10	4.2 ± 0.7	5.5 ± 0.6	0.72	0.49 to 0.85	<0.001	<0.001	<0.001
	11–20	6.1 ± 1.0	5.8 ± 0.6	0.76	0.55 to 0.87			
	21–30	8.3 ± 1.5	5.9 ± 0.7	0.66	0.41 to 0.82			
Cycle ergometer (*N* = 34)	1–10	3.8 ± 1.0	3.4 ± 0.4	0.34	0.02 to 0.61	<0.001	<0.001	<0.001
	11–20	6.6 ± 1.2	3.7 ± 0.3	0.23	−0.11 to 0.52			
Stair stepping (*N* = 36)	1–10	5.3 ± 1.2	5.1 ± 0.7	0.68	0.46 to 0.82	<0.001	<0.001	<0.001
	11–20	9.2 ± 1.9	6.6 ± 1.1	0.59	0.32 to 0.76			
Arm ergometer (*N* = 35)	1–10	3.1 ± 0.5	4.5 ± 0.6	0.74	0.54 to 0.86	<0.001	<0.001	<0.001
	11–20	4.7 ± 0.8	5.4 ± 0.7	0.73	0.52 to 0.85			

TABLE 5. Comparison of energy expenditure between indirect calorimetry and SenseWear Pro Armband™ using exercise-specific algorithms (mean ± SD).

Exercise Mode	Exercise Minutes	Energy Expenditure (kcal·min^{-1}) Measured (Indirect Calorimetry)	Estimated (Armband)	Intraclass Correlation: Correlation	95% CI	P for Repeated Measures ANOVA: Method	Workload	Method × Workload
Treadmill walking (N = 31)	1–10	4.2 ± 0.7	4.0 ± 1.0	0.78	0.60–0.89	0.17	<0.001	<0.001
	11–20	6.1 ± 1.0	6.2 ± 1.3	0.87	0.74–0.93			
	21–30	8.3 ± 1.5	7.9 ± 1.6	0.87	0.74–0.93			
Cycle ergometer (N = 18)*	1–10	3.9 ± 1.0	4.1 ± 1.2	0.84	0.63–0.94	0.91	<0.001	0.005
	11–20	6.7 ± 1.2	6.5 ± 1.5	0.89	0.74–0.96			
Stair stepping (N = 18)*	1–10	5.2 ± 1.3	5.1 ± 1.1	0.71	0.38–0.88	0.57	<0.001	0.50
	11–20	8.9 ± 2.0	8.7 ± 1.9	0.84	0.62–0.94			
Arm ergometer (N = 17)*	1–10	3.1 ± 0.5	3.0 ± 0.4	0.51	0.06–0.79	0.12	<0.001	0.54
	11–20	4.6 ± 0.6	4.4 ± 0.7	0.65	0.26–0.86			

* Indicates results for subjects on which the newly developed exercise-specific algorithm was applied.

icantly underestimated energy expenditure by 0.3 ± 0.6 kcal·min^{-1} during minutes 11–20 and 2.4 ± 0.9 kcal·min^{-1} during minutes 21–30 ($P < 0.016$). For cycle ergometer exercise, the SenseWear Pro Armband™ significantly underestimated energy expenditure during minutes 1–10 and minutes 11–20 by 0.4 ± 0.8 kcal·min^{-1} and 2.9 ± 1.1 kcal·min^{-1}, respectively ($P \leq 0.025$). During stepping exercise, there was no significant difference in energy expenditure between the two methods during minutes 1–10, with the SenseWear Pro Armband™ significantly underestimating energy expenditure by 2.6 ± 1.4 kcal·min^{-1} during minutes 11–20 ($P < 0.025$). The SenseWear Pro Armband™ significantly overestimated energy expenditure during arm ergometer exercise by 1.4 ± 0.4 kcal·min^{-1} from minutes 1–10 and by 0.7 ± 0.6 kcal·min^{-1} from minutes 11–20 ($P < 0.025$).

The results of the two-factor (method × workload) repeated measures ANOVA for each of the exercise protocols when the exercise-specific algorithms were applied to the data are presented in Table 5. Similar to the results presented using the generalized equation, significant method × workload interactions were shown for walking ($P \leq 0.001$) and cycle ergometer exercises ($P \leq 0.005$). However, the method × workload interaction was not statistically significant for stepping exercise ($P \leq 0.50$) or arm ergometer exercise ($P \leq 0.54$). *Post hoc* analyses were performed to assess differences in energy expenditure for each 10-min workload for exercises in which a significant method × workload interaction was shown (walking and cycle ergometer exercise), with the P value adjusted based on multiple comparisons according to the Bonferroni procedure. There was no significant difference in energy expenditure between the two methods during minutes 1–10 and 11–20 for the walking exercise; however, the SenseWear Pro Armband™ significantly underestimated energy expenditure by 0.4 ± 0.8 kcal·min^{-1} ($P \leq 0.016$) during minutes 21–30. For cycle exercise, posthoc analyses revealed that the difference in energy expenditure between the two methods was not statistically significant during minutes 1–10 (0.2 ± 0.6 kcal·min^{-1}) or minutes 11–20 (0.2 ± 0.6 kcal·min^{-1}).

Total energy expenditure data for indirect calorimetry and the SenseWear Pro Armband™ are presented in Figure 1A for energy expenditure estimated using the generalized equation and Figure 1B for energy expenditure estimated using the exercise-specific equations. When the generalized equation was used, the SenseWear Pro Armband™ significantly underestimated total energy expenditure by 14.9 ± 17.5 kcal (6.9 ± 8.5%) during walking exercise, 32.4 ± 18.8 kcal (28.9 ± 13.5%) during cycle ergometry, 28.2 ± 20.3 kcal (17.7 ± 11.8%) during stepping exercise, and overestimated total energy expenditure by 21.7 ± 8.7 kcal (29.3 ± 13.8%) during arm ergometer exercise ($P \leq 0.001$). When the exercise-specific equations were used, nonsignificant differences in total energy expenditure between indirect calorimetry and the SenseWear Pro Armband™ were 4.6 ± 18.1 kcal (2.8 ± 9.4%), 0.3 ± 11.3 kcal (0.9 ± 10.7%), 2.5 ± 18.3 kcal (0.9 ± 11.9%), and 3.2 ± 8.1 kcal (3.8 ± 9.9%) for the walk, cycle ergometer, step, and arm ergometer exercises, respectively.

Bland-Altman plots using data when the generalized equation was applied to the SenseWear Pro Armband™ are

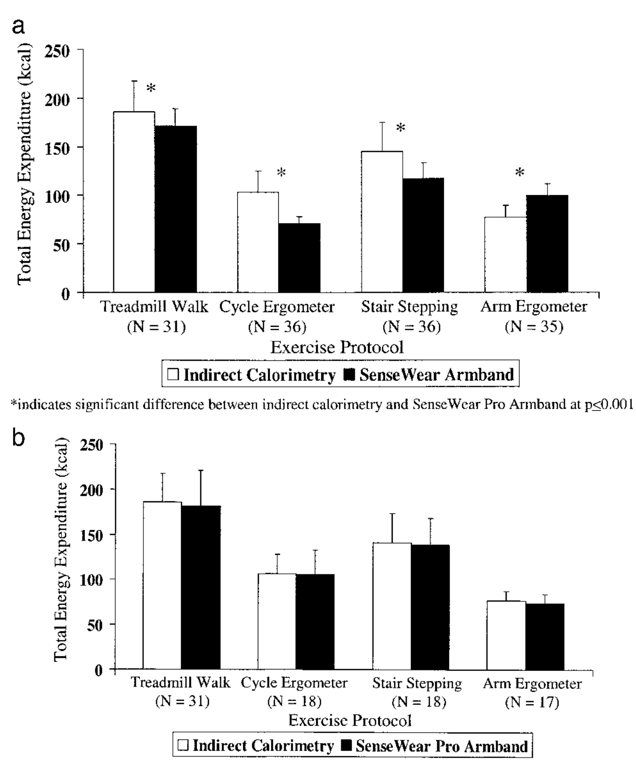

FIGURE 1—A. Total energy expenditure for each exercise protocol (mean ± SD) estimated from a generalized algorithm for the SenseWear Pro Armband™. B. Total energy expenditure for each exercise protocol (mean + SD) estimated from exercise-specific algorithms for the SenseWear Pro Armband™.

presented in Figures 2A–D. These results demonstrate that the difference between the two methods of assessing energy expenditure (indirect calorimetry and SenseWear Pro Armband™) was greatest as the magnitude of energy expenditure increased for walking, cycle ergometer, and stepping exercises, but this was not apparent for arm ergometer exercise. Figures 3A–D illustrate the Bland-Altman plots using data when the exercise-specific equations were applied to the SenseWear Pro Armband™ and demonstrate that the difference between the two methods of assessing energy expenditure does not appear to be influence by the magnitude of energy expenditure.

DISCUSSION

This study examined the validity of the SenseWear Pro Armband™ to measure energy expenditure during four different modes of exercise and across various exercise intensities in a laboratory setting. Open-circuit indirect calorimetry served as the criterion measure of energy expenditure in this study. When the generalized algorithm provided by the manufacturer was applied to the data, the SenseWear Pro Armband™ tended to significantly underestimate energy expenditure during walking, cycle ergometer, and stepping exercise, whereas significantly overestimating energy expenditure during arm ergometer exercise (see Table 4 and Fig. 1A). Moreover, as illustrated in Figures 2A–D, the magnitude of the difference in total energy expenditure between the SenseWear Pro Armband™ and indirect calorimetry appeared to increase as energy expenditure increased across individual participants in this study.

At the request of the investigators, the manufacturer developed new proprietary exercise-specific algorithms for each mode of exercise examined in this study. When the exercise-specific algorithms were applied to the data from the SenseWear Pro Armband™, the estimate of energy expenditure appeared to be improved. As illustrated in Figure 1B, there was no significant difference in total energy expenditure estimated using the SenseWear Pro Armband™ and total energy expenditure measured using indirect calorimetry during any of the modes of exercise examined in this study. Moreover, as illustrated in Figures 3A–D, the magnitude of the difference in total energy expenditure between the two methods did not appear to be influenced by the level of energy expenditure across participants in this study. To our knowledge this is the first study to compare the SenseWear Pro Armband™ to a criterion measure of energy expenditure across different modes of exercise, and the results appear to indicate that it may be necessary to use exercise-specific algorithms to improve the estimate of energy expenditure using the technology incorporated into the SenseWear Pro Armband™.

The results of this study suggest that when exercise-specific algorithms are used in combination with the SenseWear Pro Armband™, this technology may provide a more accurate estimate of energy expenditure during exer-

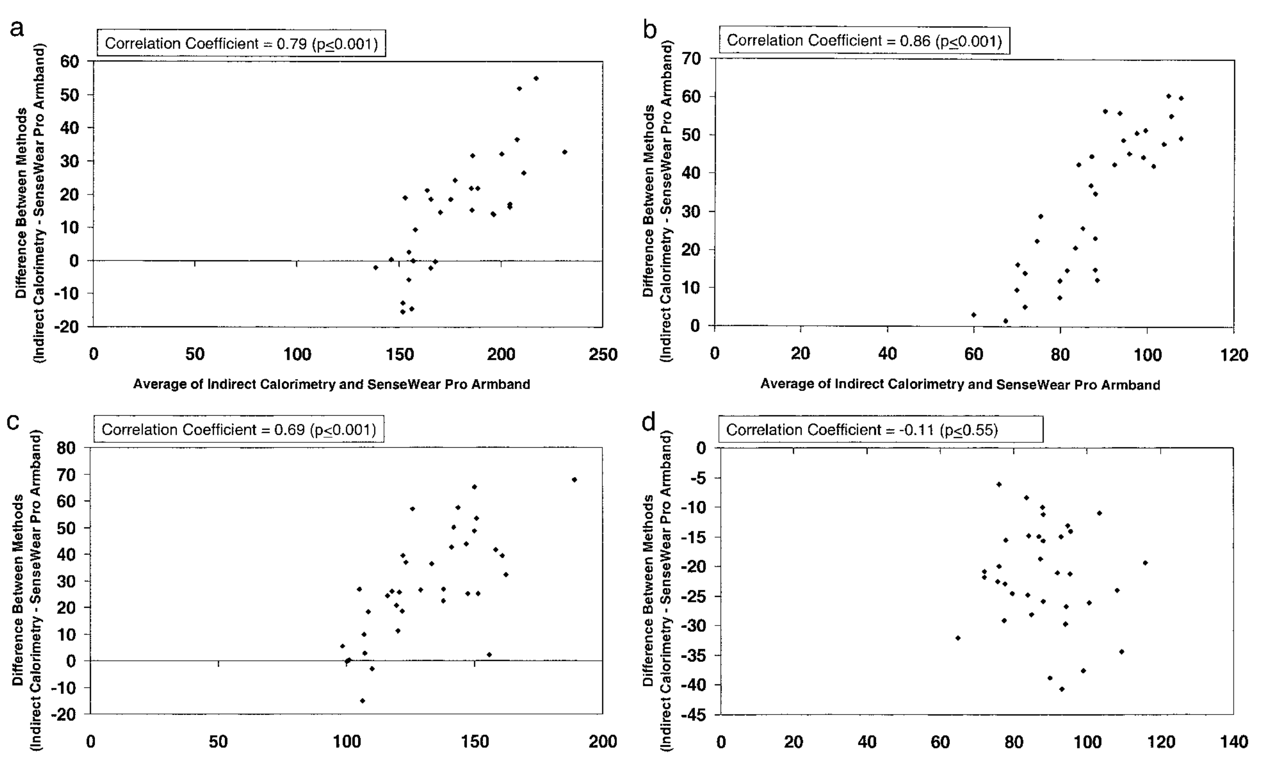

FIGURE 2—A. Bland-Altman plot for treadmill walk exercise using the generalized equation for the SenseWear Pro Armband™ to estimate total energy expenditure (*N* = 31). B. Bland-Altman plot for cycle ergometer exercise using the generalized equation for the SenseWear Pro Armband™ to estimate total energy expenditure (*N* = 34). C. Bland-Altman plot for stair step exercise using the generalized equation for the SenseWear Pro Armband™ to estimate total energy expenditure (*N* = 36). D. Bland-Altman plot for arm ergometer exercise using the generalized equation for the SenseWear Pro Armband™ to estimate total energy expenditure (*N* = 35).

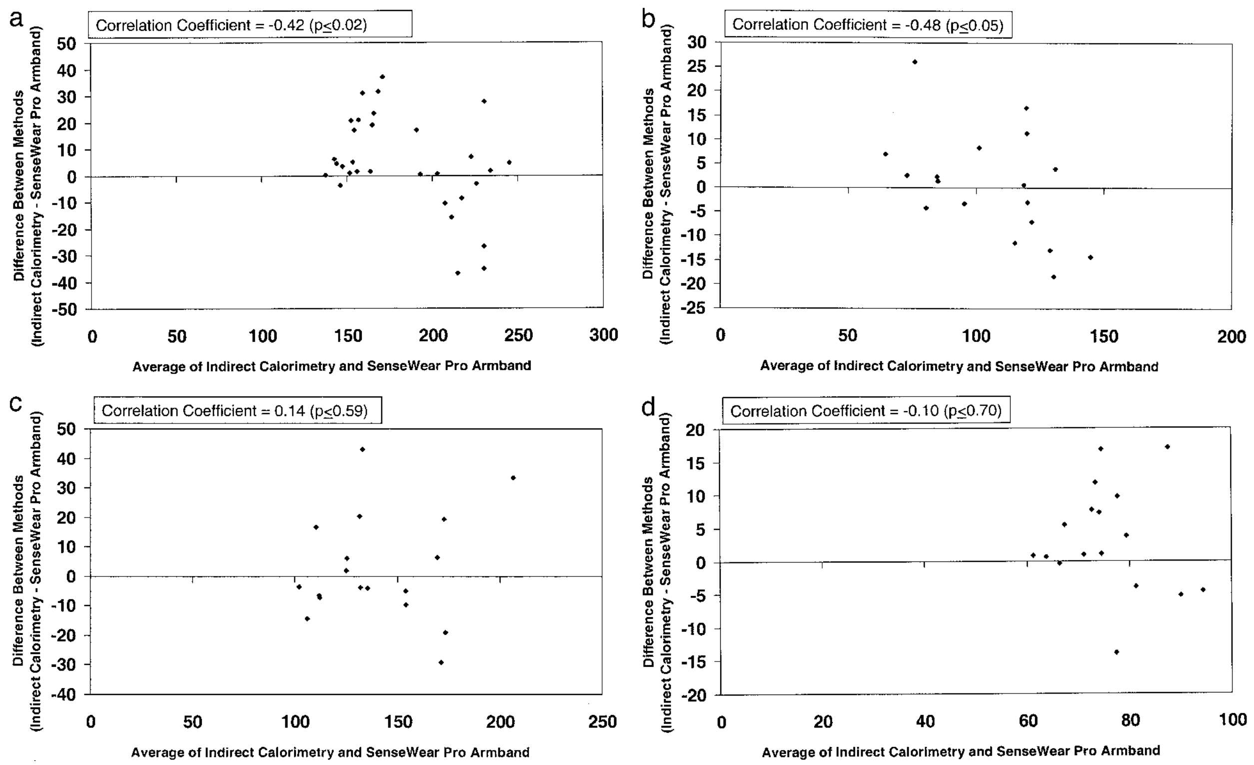

FIGURE 3—A. Bland-Altman plot for treadmill walk exercise using the newly developed exercise-specific equation for the SenseWear Pro Armband™ to estimate total energy expenditure (*N* = 31). B. Bland-Altman plot for cycle ergometer exercise using the newly developed exercise-specific equation for the SenseWear Pro Armband™ to estimate total energy expenditure (*N* = 18). C. Bland-Altman plot for treadmill stair step exercise using the newly developed exercise-specific equation for the SenseWear Pro Armband™ to estimate total energy expenditure (*N* = 18). D. Bland-Altman plot for arm ergometer exercise using the newly developed exercise-specific equation for the SenseWear Pro Armband™ to estimate total energy expenditure (*N* = 17).

cise than other commonly used portable energy expenditure monitors. For example, in a study comparing a triaxial accelerometer to indirect calorimetry, Jakicic et al. (8) reported that the accelerometer underestimated energy expenditure by a total of 30–50 kcal for 30 min of walking exercise, 87–89 kcal for 20 min of cycling exercise, and 44–51 kcal for 20 min of stepping exercise. Using similar exercise protocols, the current study showed that the difference in total energy expenditure between indirect calorimetry and the SenseWear Pro Armband™ was 4.6 ± 18.1 kcal for walking exercise, 2.5 ± 18.3 kcal for stepping exercise, and 0.3 ± 11.3 kcal for cycle ergometer exercise. Of interest is that an accelerometer, which is commonly worn at the level of the waist, is unlikely to accurately estimate energy expenditure during activities, which rely primarily on upper extremity movement (i.e., arms). In contrast, this study showed that the SenseWear Pro Armband™ was able to provide an accurate estimate of energy expenditure during arm exercise. Although these initial results suggesting that when exercise-specific algorithms are used, the SenseWear Pro Armband™ may provide a more accurate estimate of energy expenditure than accelerometry, these findings require confirmation from additional studies involving both laboratory and free-living paradigms.

Despite the promising findings demonstrated in this study, there are methodological limitations that need to be considered. In the current study, the investigators requested that exercise-specific algorithms (walk, cycle, step, and arm) be developed by the manufacturer and applied to the raw data collected during each of these exercises to estimate energy expenditure. Although the use of exercise-specific algorithms did improve the accuracy of SenseWear Pro Armband™ to estimate energy expenditure in this initial laboratory-based study, this may prove problematic under free-living conditions that are less controlled. For example, if exercise-specific algorithms are necessary, it is unclear whether the manufacturer can program the SenseWear Pro Armband™ to automatically switch between different mode-specific algorithms when necessary or whether this will have to be initiated by the individual wearing the armband. The need for the user to initiate a change in the algorithm based on the activity that is being performed may make this device less useful for assessing energy expenditure during periods of free-living activity. An alternative solution may be for the manufacturer to enhance the accuracy of the generalized algorithm to provide an estimate of energy expenditure across all modes and intensities of activities. However, as shown with other portable devices for assessing energy expenditure such as heart rate monitors (10), global algorithms may be less accurate than algorithms based on specific criteria, and this is supported by the results from this current study.

An additional limitation of this study is that the accuracy of the SenseWear Pro Armband™ was examined during specific exercise modes (walking, cycling, stepping, and arm ergometry), exercise intensities (light to moderate intensity; see Table 3), and exercise durations (20–30 min; see Table 1). However, it is unclear whether similar findings would be observed during other modes of activity (e.g., lifestyle activities), more vigorous intensities of activity, activity that is either shorter or longer in duration, or under different environmental conditions. Because this was a laboratory-based study, subjects only had to wear the armband for a period of 30–45 min. It cannot be determined from this study whether individuals would be willing to wear the armband for periods of time that are significantly longer in duration. Moreover, this study was conducted in a laboratory setting and used indirect calorimetry as the criterion measure of energy expenditure. Future studies should consider examining energy expenditure during free-living conditions along with doubly labeled water as the criterion measure of energy expenditure.

Based on the results of this study, it is also unclear whether the results are generalizable across different population groups. For example, this study examined the accuracy of the SenseWear Pro Armband™ in relatively young, normal weight adults (see Table 2). It is unclear whether similar results would be observed in individuals of different ages, body weights, or even levels of fitness. The SenseWear Pro Armband™ does incorporate heat flux into the proprietary algorithm to estimate energy expenditure, and it is possible that higher levels of body fatness may impact the accuracy of the existing algorithms.

Despite these potential limitations, this study provides initial evidence that the SenseWear Pro Armband™ along with exercise-specific algorithms can provide an accurate estimate of energy expenditure. This is an important first step in the development of this technology. Based upon the results of this present investigation, the SenseWear Pro Armband™ may have the ability to provide a more accurate alternative to other more commonly used portable energy expenditure devices. However, it may be necessary for the commercially available device to incorporate exercise-specific algorithms into the estimate of energy expenditure and to develop a method for the device to switch between exercise-specific algorithms with limited burden on the user. The ability to accurately assess energy expenditure in free-living individuals may enhance the knowledge related to the link between the dose of physical activity and health status, along with improving the understanding of how energy expenditure impacts energy balance related to weight control and chronic diseases such as diabetes mellitus.

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