Comparison of Activity Monitors to Estimate Energy Cost of Treadmill Exercise

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ABSTRACT

KING, G. A., N. TORRES, C. POTTER, T. J. BROOKS, and K. J. COLEMAN. Comparison of Activity Monitors to Estimate Energy Cost of Treadmill Exercise. *Med. Sci. Sports Exerc.*, Vol. 36, No. 7, pp. 1244–1251, 2004. **Purpose:** To evaluate the validity of five physical activity monitors available for research: the CSA, the TriTrac-R3D, the RT3, the SenseWear Armband, and the BioTrainer-Pro. **Methods:** A total of 10 healthy men and 11 healthy women performed 10 min of treadmill walking at 54, 80, and 107 m·min^{-1} and treadmill running at 134, 161, 188, and 214 m·min^{-1}. The CSA, TriTrac-R3D, RT3, and BioTrainer-Pro accelerometers were placed side by side bilaterally at the waist in the axillary position, and the SenseWear Armband monitors were placed bilaterally on the posterior portion of each arm in the mid-humeral position. Simultaneous measurements of body motion and indirect calorimetry were continuously recorded during all exercise. Data were analyzed with repeated measures ANOVA and pairwise Bonferroni-adjusted estimated marginal means. **Results:** There was no significant difference in the mean energy expenditure (EE) recorded bilaterally by any of the monitors ($P > 0.05$) at any treadmill speed. The SenseWear Armband, the TriTrac-R3D, and the RT3 had significant increases in mean EE across all walking and running speeds ($P < 0.05$). Below 161 m·min^{-1}, the mean EE recorded by the BioTrainer-Pro and the CSA increased significantly ($P < 0.001$); however, there was no significant difference ($P > 0.10$) in mean EE recorded by either monitor for speeds above 161 m·min^{-1}. In general, all monitors overestimated EE at most treadmill speeds when compared with indirect calorimetry ($P < 0.001$), except for the CSA which underestimated EE at the lowest and highest speeds. **Conclusion:** The CSA was the best estimate of total EE at walking and jogging speeds, the TriTrac-R3D was the best estimate of total EE at running speeds, and the SenseWear Armband was the best estimate of total EE at most speeds. **Key Words:** ACCELEROMETER, WALKING, RUNNING, MEASUREMENT, MOTION SENSOR, VALIDITY

Recent statistics indicate that 13% of U.S. children and adolescents are overweight and 61% of U.S. adults are considered overweight or obese (24). A number of pathologic conditions and health risks are associated with being overweight or obese affecting both men and women among all racial and ethnic groups (24). A person with a sedentary lifestyle has a twofold greater risk for becoming overweight or obese, and physical inactivity plays a key role in premature death (24). Despite the available research and the known benefits of physical activity, 60% of people do not accumulate a sufficient amount of physical activity to derive health benefits, and 25% do not engage in any physical activity during their leisure time (6,24). Because many health experts attribute the current U.S. obesity epidemic to physical inactivity (18,24), a priority has been placed on the use of valid and reliable measures for all levels of physical activity to assess the health impact of increasing physical activity in a variety of populations (5,7,24).

Historically, investigators have relied on self-report when attempting to quantify physical activity (22). However, intrinsic validity and reliability issues with self-report support the use of objective measures of physical activity. Some objective measures have included heart rate monitors, laboratory observation, stable isotope ingestion, and motion sensing devices. The use of heart rate data to quantify physical activity has inherent problems that make it impractical (1,20), and stable isotopes, while quite valid and reliable, are cost prohibitive (1,7,20). Motion sensors have the potential to be a cost-effective, direct measure of physical activity with a low response burden for participants (1,2,20).

An accelerometer is a type of motion sensor capable of detecting acceleration and deceleration in one or more directions of movement. A uniaxial accelerometer measures acceleration in the vertical plane, whereas biaxial and triaxial accelerometers are sensitive to movements in two and three dimensions, respectively. When these devices detect movement, an electric current is generated within the motion sensor that is proportional to the degree of acceleration (20). Because acceleration increases in several dimensions with faster movements, theoretically, accelerometers should accurately determine energy expenditure (EE) across a wide range of exercise intensities.

Two accelerometers that have been used extensively by researchers to index physical activity are the Computer

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Science Applications (CSA), Inc. activity monitor (Shalimar, FL) and the TriTrac-R3D (Professional Products Inc., Madison, WI). Each of these monitors has been used in more than 20 studies published in refereed journals. The CSA is lightweight and compact in size but is a uniaxial accelerometer and may not be sensitive to movements in all planes of motion. The TriTrac-R3D is a triaxial accelerometer but is cumbersome in size and can obstruct movement when worn properly. Previous research, which included both the CSA and the TriTrac-R3D, reported these monitors acceptable for estimating EE under laboratory conditions (23,26,27), whereas EE was frequently underestimated during free-living conditions (8,12,14,15,26).

The quantification of physical activity continues to be problematic and thus there is ongoing development of new technologies to precisely measure human movement to infer something about EE. Three recently introduced motion sensors, the RT3 Triaxial Research Tracker (RT3; Stayhealthy Inc., Monrovia, CA), the BioTrainer-Pro (IM Systems, Baltimore, MD), and the SenseWear Armband (BodyMedia Inc., Pittsburgh, PA), may provide researchers with additional tools for objectively measuring physical activity. The purpose of this study was to assess the ability of the CSA, the TriTrac-R3D, the RT3, the BioTrainer-Pro, and the SenseWear Armband to accurately estimate the energy cost of various speeds of treadmill walking and running measured by indirect calorimetry.

METHODS

Physical Activity Monitors

The physical activity monitors used for this study were the CSA, now called the Actigraph (Model 7164, Shalimar, FL; MTI Actigraph, Fort Walton Beach, FL), the TriTrac-R3D, the RT3, the BioTrainer-Pro, and the SenseWear Armband. Detailed descriptions of the CSA (9) and the TriTrac-R3D (16) are provided elsewhere. Each model of physical activity monitor had associated research software with computer interface, download, and export capabilities (CSA: v2.2; TriTrac-R3D: v3.0; RT3: v1.0.0.7; BioTrainer-Pro: v6.0.0.6; and SenseWear Armband: v3.0). A 1-min sampling interval was used for all devices in this study.

The CSA is a uniaxial accelerometer with a minimum sampling interval of 1 s, capable of storing up to 22 d of 1-min data. For this study, total EE ($kcal \cdot min^{-1}$) was calculated from the recorded CSA activity counts using the manufacturer provided equation ($kcal = 0.0000191 \cdot$ activity counts $\cdot$ body mass in kg) and the equation suggested by Freedson and colleagues (9) [$kcal = (0.00094 \cdot$ activity counts$) + (0.1346 \cdot$ body mass in kg$) - 7.37418$].

Introduced to the public as the next generation of the TriTrac-R3D (www.stayhealthy.com), the RT3 measures three-dimensional piezoelectric signals, has a sampling interval of 1 s to 1 min, data storage capabilities up to 21 d, and is approximately one-third the size of the TriTrac-R3D. An event marker allows the user to timestamp the start and end of activity. The RT3 provides single vector and vector magnitude activity data and uses proprietary algorithms to derive total kilocalories and activity kilocalories per sampling interval.

The BioTrainer-Pro is a biaxial accelerometer with a sampling interval range from 15 s to 5 min and is capable of storing up to 112 d of data. The data are digitally sampled, accumulated in 15-s, 30-s, 1-min, 2-min, or 5-min intervals and saved as either absolute "*g*" units or kilocalories of activity per sampling interval.

The BioTrainer-Pro requires the user to specify the sensitivity level of measurement before data acquisition based on the intensity of the anticipated activity. To determine the appropriate level of sensitivity for the current study, pilot investigations of treadmill exercise were conducted at each of the BioTrainer-Pro's six sensitivity options (×1, ×2, ×4, ×10, ×20, and ×40). The results of these pilot trials indicated that the ×1 setting lacked the resolution necessary to delineate treadmill walking at 54 $m \cdot min^{-1}$, whereas the ×10, ×20, and ×40 settings exceeded the maximum reportable values at 214 $m \cdot min^{-1}$. Therefore, to maximize the resolution of data across the entire range of treadmill speeds and remain within the maximum reportable limits of the BioTrainer-Pro software, the ×4 sensitivity setting was used for all subsequent testing.

The SenseWear Armband can store up to 5 d of data and contains a biaxial accelerometer, a heart rate receiver, and a thermocoupler having the unique capability of measuring heat production. The body monitor itself is a wireless armband worn in contact with the upper arm skin surface and allows for user-initiated timestamp event markers. In conjunction with simple body descriptors, the SenseWear Armband records approximately 21 measurement parameters for the estimation of total EE derived from proprietary algorithms. The current study used longitudinal and transverse acceleration, and the heat flux between skin temperature and near body ambient temperature to estimate total EE.

Participants

Twenty-one volunteers ($N = 10$ men; $N = 11$ women) from the El Paso, TX, community participated in two separate laboratory testing sessions. Before any data collection, participants received a thorough explanation of the procedures and risks involved with this project and provided written consent to participate. To ensure each participant's ability to complete the physical activity monitor validation test (session 2), a $\dot{V}O_{2peak}$ greater than 50 $mL \cdot kg^{-1} \cdot min^{-1}$ was required for participation. This fitness level was verified in session one. All procedures were approved by the University of Texas at El Paso Institutional Review Board for human subjects research.

Experimental Protocols

Body composition. After completing informed consent and a health status questionnaire, height was measured to the nearest 0.5 cm using a calibrated stadiometer (Novel Products, Inc, Rockton, IL), weight was measured to the nearest 0.1 kg using an electronic platform scale (Tanita

Corporation, Japan), and percentage of body fat was estimated by whole body plethysmography (BOD POD Body Composition System, Life Measurement Instruments, Concord, CA; 17).

Resting metabolic rate (RMR). For the measurement of RMR, participants arrived at the laboratory in the morning, after 6–8 h of sleep, at least 12 h postprandial, and having refrained from alcohol consumption and physical activity for 24 h before reporting for the test. Participants were fitted with a mouthpiece connected to a large two-way nonrebreathing valve (Hans Rudolph Inc., Kansas City, MO) and allowed to rest for 20 min lying in a comfortable, reclined position. Expired gases were then collected for 30 min and analyzed for the fractional concentration of oxygen and carbon dioxide using an automated metabolic measurement system (TrueMax 2400, Consentius Technologies, Sandy, UT) (3).

Immediately before every metabolic test, the flowmeter was calibrated using a 3-L calibration syringe (Hans Rudolph Inc.), and the gas analyzers were calibrated using a two-point calibration method against certified gases of known concentration (16% O_2, 4% CO_2). Metabolic gas volumes were derived by the Fick equation (19), and kilocalories were calculated using the following equation: kcal $= \dot{V}O_2$ ($L \cdot min^{-1}$) $\times$ 4.825 ($kcal \cdot L^{-1}$ O_2; 13). The initial 10 min of expired gas data were discarded, and only the final 20 min of the RMR test were averaged and recorded as RMR. Resting metabolism was later subtracted from exercise metabolism recorded during the physical activity monitor validation protocol, described below, to derive the metabolic cost of activity.

Peak oxygen uptake test. After the RMR test, each participant performed a peak oxygen uptake ($\dot{V}O_{2peak}$) test on a calibrated motor driven treadmill (Q65, Quinton Instrument Co., Bothell, WA). The initial speed of the treadmill was 161 $m \cdot min^{-1}$ for women and 188 $m \cdot min^{-1}$ for men with an initial grade of 0%. The speed was then increased 13 $m \cdot min^{-1}$ each minute up to a maximum speed of 201 $m \cdot min^{-1}$ for women and 214 $m \cdot min^{-1}$ for men. The grade of the treadmill was then increased 1% each minute until volitional exhaustion. Expired gases were collected and analyzed continuously using the previously described metabolic measurement system and $\dot{V}O_{2peak}$ was defined as the highest oxygen uptake value achieved during any 15-s interval of the test.

Physical activity monitor validation test. Participants were scheduled to return to the laboratory within 1 wk of the RMR and $\dot{V}O_{2peak}$ tests to complete a single monitor validity testing session while simultaneously wearing the CSA, TriTrac-R3D, RT3, BioTrainer-Pro, and SenseWear Armband physical activity monitors. Two of each physical activity monitor were worn with one on the right and one on the left sides of the body, positioned according to the manufacturer's recommendations. The CSA was located at the waist in the anterior axillary position, the TriTrac-R3D was located at the waist in the mid-axillary position, the RT3 was located at the waist between the CSA and TriTrac-R3D, the BioTrainer-Pro was placed at the waist in the posterior axillary position, and the SenseWear Armband was mounted on the posterior aspect of each participant's arm in the mid-humeral position. Adjacent devices were not in contact with each other.

All physical activity monitors were numbered, and right and left side placement was counterbalanced within each pair of monitors across all participants. Before each test, each activity monitor was initialized with test and participant information (height, weight, age, gender) using a single desktop computer. The use of a single computer allowed each activity monitor to be aligned to a single clock so that all monitor data could be synchronized to within 1 s. Each participant began slow walking on the treadmill and then progressed through fast running. Simultaneous measurements of body motion and indirect calorimetry were recorded continuously during the validation protocol using the CSA, TriTrac-R3D, RT3, BioTrainer-Pro, and SenseWear Armband physical activity monitors and the previously described metabolic measurement system.

Participants performed treadmill walking at 53, 80, and 107 $m \cdot min^{-1}$; and treadmill running at 134, 161, 188, and 214 $m \cdot min^{-1}$ in sequence (2, 3, 4, 5, 6, 7, and 8 mph, respectively). Each speed was maintained for 10 min with a minimum of 2-min rest between each treadmill speed. During the rest interval, participants were allowed to breathe without the mouthpiece and drink water but were not allowed to eat food or drink any calorie-containing beverages.

Statistical Analysis

Statistical comparisons were performed using the software package Systat Version 8.0 (SPSS, Chicago, IL). Indirect calorimetry (IC) values were established as the criterion EE measure and all EE values are reported as kilocalories per minute. To ensure steady state oxygen uptake values, only the final 7 min of each exercise stage were used for data analyses. All motion sensor data were time-matched to within 1 s of IC. For IC measures, EE values were recorded as total EE and activity EE (total EE − RMR EE) for comparison with the monitor findings. For both the TriTrac-R3D and the RT3, vector magnitude counts, activity EE, and total EE were used for data analyses. For the CSA, total EE derived from the manufacturer provided algorithm and total EE estimated with the Freedson equation (9) were used. The BioTrainer-Pro was analyzed using its activity EE, and the SenseWear Armband data were analyzed using the longitudinal and transverse axes counts, as well as estimates of total EE. The recorded EE values for the TriTrac-R3D, RT3, BioTrainer-Pro, and SenseWear Armband were derived from each physical activity monitor's associated software and proprietary formulas.

Side and speed differences among monitor indicators were analyzed using a 2 $\times$ (2) $\times$ (7) mixed ANOVA with one between subjects factor of gender (men, women) and two within subjects factors of side (left, right) and treadmill speed (54, 80, 107, 134, 161, 188, and 214 $m \cdot min^{-1}$). Significant interactions were further analyzed using dependent or independent sample *t*-tests as appropriate. No cor-

TABLE 1. Means ± SD for all monitors worn by men in the study; results are shown for each speed separately.

	54 m·min^{-1}	80 m·min^{-1}	107 m·min^{-1}	134 m·min^{-1}	161 m·min^{-1}	188 m·min^{-1}	214 m·min^{-1}
CSA (N = 9)							
Activity counts	995 ± 376	2823 ± 634	4877 ± 906	8572 ± 1353	9227 ± 1228	9306 ± 1313	9546 ± 1375
Total EE	1.31 ± 0.51	3.74 ± 0.88	6.41 ± 1.15	11.30 ± 1.50	12.14 ± 1.74	12.20 ± 1.48	12.59 ± 1.49
Freedson total EE	2.85 ± 0.91	4.63 ± 1.00	6.50 ± 1.07	10.04 ± 1.10	10.59 ± 1.29	10.67 ± 1.09	10.95 ± 1.06
BioTrainer (N = 10)							
Activity EE	2.83 ± 0.56	5.02 ± 0.67	8.34 ± 1.05	17.63 ± 2.77	18.83 ± 2.72	18.67 ± 3.71	19.60 ± 5.36
TriTrac (N = 10)							
Vecmag counts	963 ± 131	1595 ± 264	2422 ± 306	4461 ± 653	5068 ± 741	5406 ± 649	5451 ± 805
Activity EE	2.48 ± 0.39	4.11 ± 0.85	6.24 ± 0.94	11.50 ± 1.83	13.12 ± 2.43	13.98 ± 2.26	14.10 ± 2.55
Total EE	3.78 ± 0.44	5.41 ± 0.89	7.54 ± 0.97	12.79 ± 1.86	14.42 ± 2.48	15.28 ± 2.31	15.40 ± 2.60
RT3 (N = 9)							
Vecmag counts	1163 ± 183	1830 ± 310	2679 ± 358	4533 ± 443	5252 ± 514	5733 ± 569	5951 ± 563
Activity EE	3.00 ± 0.45	4.75 ± 1.05	7.00 ± 1.16	11.72 ± 1.46	13.60 ± 1.90	14.86 ± 2.12	15.41 ± 2.18
Total EE	4.30 ± 0.48	6.06 ± 1.09	8.32 ± 1.02	13.02 ± 1.51	14.91 ± 1.96	16.16 ± 2.18	16.71 ± 2.22
SenseWear (N = 8)							
Long axis counts	161 ± 29	217 ± 30	351 ± 68	1232 ± 135	1473 ± 231	1584 ± 387	1819 ± 249
Trans axis counts	94 ± 18	129 ± 19	233 ± 21	767 ± 171	920 ± 263	997 ± 351	1116 ± 234
Total EE	5.26 ± 0.43	5.99 ± 0.46	7.37 ± 0.51	13.26 ± 1.31	14.50 ± 1.81	14.63 ± 3.27	16.13 ± 1.49
IC (N = 10)							
$\dot{V}O_2$ L·min^{-1}	0.68 ± 0.07	.85 ± 0.09	1.25 ± 0.17	1.96 ± 0.24	2.33 ± 0.34	2.68 ± 0.36	3.06 ± 0.36
Activity EE	2.02 ± 0.25	2.82 ± 0.34	4.78 ± 0.79	8.25 ± 1.03	10.01 ± 1.51	11.75 ± 1.61	13.59 ± 1.65
Total EE	3.31 ± 0.33	4.12 ± 0.45	6.08 ± 0.81	9.55 ± 1.15	11.30 ± 1.63	13.04 ± 1.73	14.88 ± 1.77

Counts (accelerometric counts), vector magnitude (vecmag), energy expenditure (EE), Freedson EE (9), EE (kcal·min^{-1}).

rections were made for multiple comparisons of differences in speed as it was hypothesized that there would be no differences for any of the monitors. Each physical activity indicator for every monitor was treated as a separate dependent measure in these ANOVA (i.e., monitor counts, activity kcal·min^{-1}, and total kcal·min^{-1} were all analyzed separately).

Differences among monitors' estimates of activity EE and total EE as compared with IC values were analyzed for each treadmill speed using separate two-way mixed MANOVA with a between subjects factor of gender (men, women) and two dependent measures of monitor EE and IC EE. Bonferroni adjustments were made for the number of MANOVA conducted for activity EE values (four) and total EE values (six). Therefore, the significance value for activity EE comparisons was $P < 0.013$ and for total EE comparisons was $P < 0.008$. Finally, bivariate Pearson's product moment correlations were generated between each monitor indicator and each IC measure.

RESULTS

Means and SD for each monitor during each testing speed are shown in Tables 1 and 2. Men ($N = 10$) were on average 25.2 ± 4.5 yr old, weighed 69.5 ± 6.2 kg, had an average $\dot{V}O_{2peak}$ of 62.7 ± 10.1 mL·kg^{-1}·min^{-1}, and had a mean percentage body fat of 9.0 ± 7.8%. Women ($N = 11$) were on average 24.7 ± 5.4 yr old, weighed 59.5 ± 6.1 kg, had an average $\dot{V}O_{2peak}$ of 55.8 ± 4.3 mL·kg^{-1}·min^{-1}, and had a mean percentage body fat of 17.0 ± 6.5%. One CSA ($N = 9$), one RT3 ($N = 9$), and two SenseWear Armbands ($N = 8$) failed during men's testing and one SenseWear Armband ($N = 10$) failed during women's testing.

Side differences. There were no significant differences between right and left monitor outputs for the CSA (all indicators), TriTrac-R3D (all indicators), RT3 (all indicators), BioTrainer-Pro, and SenseWear estimated kilocalories per minute ($P > 0.05$). However, the SenseWear Armband had a two-way interaction between gender and side for both the longitudinal ($F(1,17) = 4.84$; $P = 0.04$) and transverse ($F(1,17) = 4.49$; $P = 0.049$) axes, such that women had longitudinal axis side differences whereas men did not, and men had transverse axis side differences whereas women did not. For the remainder of all analyses, data were averaged across left and right sides for all monitors. Tables 1–3 and Figures 1 and 2 reflect an average value for monitors placed on left and right sides of the body.

Speed differences. As a demonstration that EE changed with increasing speed in all participants, there was a main effect of speed on IC $\dot{V}O_2$ liters per minute ($F(6,114) = 665.28$; $P < 0.001$), IC activity EE ($F(6,114) = 665.28$; $P < 0.001$), and IC total EE ($F(6,114) = 665.28$; $P < 0.001$), such that there were steady increases in each marker from 54 to 214 m·min^{-1} for each participant (see activity and total EE depicted in Figs. 1 and 2, respectively).

There was a significant effect of speed for CSA activity counts ($F(6,108) = 272.14$; $P < 0.001$), estimated total EE ($F(6,108) = 247.68$; $P < 0.001$), and Freedson equation estimated total EE ($F(6,108) = 272.14$; $P < 0.001$). There was a steady increase for all CSA indicators with speed from 54 to 161 m·min^{-1} ($P < 0.001$); however, there were no significant differences in any of the CSA indicators from 161 to 188 m·min^{-1} ($P = 0.34$) or from 188 to 214 m·min^{-1} ($P = 0.41$; Fig. 2). The BioTrainer-Pro also recorded increased estimated activity EE as a result of treadmill speed changes ($F(6,114) = 223.81$; $P < 0.001$), with steady increases from 54 to 161 m·min^{-1}, no change from 161 to 188 m·min^{-1} ($P = 0.97$), and a slight increase from 188 to 214 m·min^{-1} ($P = 0.048$; Fig. 1).

These results were similar for the TriTrac-R3D; with main effects for speed in vector magnitude counts ($F(6,114) = 641.50$; $P < 0.001$), estimated activity EE ($F(6,114) = 413.09$; $P < 0.001$), and estimated total EE ($F(6,114) = 412.99$; $P < 0.001$). Unlike the CSA and the BioTrainer-Pro, all TriTrac-R3D indicators had steady changes with each increase in treadmill speed (Figs. 1 and 2). However, the increases between 161 and 188 m·min^{-1} (P = 0.03–

TABLE 2. Means ± SD for all monitors worn by women in the study; results are shown for each speed separately.

	54 m·min^{-1}	80 m·min^{-1}	107 m·min^{-1}	134 m·min^{-1}	161 m·min^{-1}	188 m·min^{-1}	214 m·min^{-1}
CSA (N = 11)							
Activity counts	1070 ± 201	2924 ± 391	5009 ± 700	9346 ± 1601	9782 ± 2045	9475 ± 1976	9125 ± 1805
Total EE	1.19 ± 0.31	3.24 ± 0.69	5.56 ± 1.23	10.37 ± 2.53	10.86 ± 2.97	10.53 ± 2.85	10.14 ± 2.62
Freedson total EE	1.42 ± 1.21	3.16 ± 1.25	5.13 ± 1.43	9.20 ± 2.04	9.61 ± 2.31	9.32 ± 2.35	8.99 ± 2.22
BioTrainer (N = 11)							
Activity EE	2.65 ± 0.55	4.39 ± 0.55	7.39 ± 0.88	14.77 ± 2.76	15.75 ± 2.96	15.86 ± 4.02	16.34 ± 3.84
TriTrac (N = 11)							
Vecmag counts	1102 ± 195	1756 ± 219	2795 ± 310	4828 ± 502	5339 ± 636	5416 ± 296	5697 ± 346
Activity EE	2.33 ± 0.57	3.71 ± 0.68	5.91 ± 1.03	10.27 ± 2.05	11.38 ± 2.59	11.47 ± 1.60	12.07 ± 1.75
Total EE	3.38 ± 0.62	4.76 ± 0.73	6.96 ± 1.07	11.32 ± 2.10	12.43 ± 2.64	12.52 ± 1.65	13.11 ± 1.80
RT3 (N = 10)							
Vecmag counts	1262 ± 231	2045 ± 358	2970 ± 317	4880 ± 617	5389 ± 574	6029 ± 791	6533 ± 903
Activity EE	2.63 ± 0.58	4.22 ± 0.68	6.17 ± 0.94	10.16 ± 1.76	11.26 ± 2.05	12.61 ± 2.56	13.67 ± 2.88
Total EE	3.67 ± 0.61	5.26 ± 0.68	7.22 ± 0.97	11.21 ± 1.80	12.30 ± 2.09	13.65 ± 2.60	14.71 ± 2.92
SenseWear (N = 11)							
Long axis counts	187 ± 38	230 ± 36	380 ± 49	1342 ± 251	1495 ± 268	1720 ± 289	1953 ± 321
Trans axis counts	111 ± 20	169 ± 21	292 ± 46	774 ± 138	873 ± 173	986 ± 203	1109 ± 252
Total EE	4.34 ± 0.49	4.83 ± 0.69	6.07 ± 0.62	10.97 ± 1.47	11.70 ± 1.49	12.61 ± 1.53	13.44 ± 1.70
IC (N = 11)							
$\dot{V}O_2$ L·min^{-1}	0.56 ± 0.06	0.69 ± 0.06	0.97 ± 0.06	1.59 ± 0.24	1.84 ± 0.27	2.15 ± 0.30	2.51 ± 0.33
Activity EE	1.66 ± 0.18	2.27 ± 0.17	3.63 ± 0.26	6.67 ± 1.08	7.90 ± 1.24	9.41 ± 1.36	11.12 ± 1.50
Total EE	2.73 ± 0.27	3.34 ± 0.27	4.70 ± 0.28	7.74 ± 1.15	8.97 ± 1.33	10.48 ± 1.45	12.18 ± 1.59

Counts (accelerometric counts), vector magnitude (vecmag), energy expenditure (EE), Freedson EE (9), EE (kcal·min^{-1}).

0.049), and 188 and 214 m·min^{-1} (P = 0.03–0.049) were somewhat attenuated. Main effects of speed were also seen for the same indicators in the RT3: vector magnitude (F(6,102) = 433.86; P < 0.001), estimated activity EE (F(6,102) = 844.62; P < 0.001), and estimated total EE (F(6,102) = 325.05; P < 0.001). All RT3 indicators had steady increases with each treadmill speed, with the increase from 188 to 214 m·min^{-1} also somewhat attenuated (P = 0.003 to 0.006; Figs. 1 and 2).

Finally, the SenseWear Armband indicators also changed significantly with differing speeds. The longitudinal axis activity counts (F(6,102) = 455.59; P < 0.001), the transverse axis activity counts (F(6,102) = 206.02; P < 0.001), and estimated total EE (F(6,102) = 626.20; P < 0.001) all increased steadily from 54 to 214 m·min^{-1} (Fig. 2).

Monitor differences. Activity EE findings across all treadmill speeds are shown in Figure 1. All monitors significantly overestimated activity EE at all treadmill speeds (P < 0.001) except for the TriTrac-R3D estimates at 214 m·min^{-1}, which were similar to IC activity EE (P = 0.027).

Findings for estimates of total EE for all treadmill speeds are shown in Figure 2. The CSA total EE values were similar to IC total EE for 80 m·min^{-1} (P = 0.18), 107 m·min^{-1} (P = 0.02), 161 m·min^{-1} (P = 0.01), and 188 m·min^{-1} (P = 0.41). Total EE was *underestimated* by the CSA at 54 m·min^{-1} (P < 0.001) and 214 m·min^{-1} (P < 0.001), and *overestimated* at 134 m·min^{-1} (P < 0.001). The findings with the Freedson equation were similar, except that the CSA was similar to IC total EE for 134 m·min^{-1} (P = 0.01). The RT3 and SenseWear Armband overestimated total EE at all treadmill speeds as compared with IC (P < 0.001). The TriTrac-R3D overestimated total EE at all speeds (P < 0.001) except 214 m·min^{-1}, where there was no significant difference between the TriTrac-R3D and IC total EE (P = 0.03).

Effects of gender. As expected there was a main effect of gender for IC $\dot{V}O_2$ liters per minute (F(1,19) = 17.57; P < 0.001), IC activity EE (F(1,19) = 16.78; P < 0.001), and IC total EE (F(1,19) = 17.57; P < 0.001), such that women had lower values than men for all indicators. There was also a main effect of gender for the following activity monitor indicators: CSA Freedson equation estimated total EE (F(1,18) = 4.57; P = 0.047), BioTrainer-Pro estimated activity EE (F(1,19) = 4.90; P = 0.04), TriTrac-R3D estimated activity EE (F(1,19) = 5.07; P = 0.04), RT3 estimated activity EE (F(1,17) = 4.81; P = 0.04), RT3 estimated total EE (F(1,17) = 6.39; P = 0.02), and SenseWear Armband estimated total EE (F(1,17) = 16.91; P = 0.001). For all of these indicators, women had lower values than men.

In addition to the main effects of gender, there was an expected interaction of gender and speed for IC $\dot{V}O_2$ liters per minute (F(6,114) = 7.28; P < 0.001), IC activity EE (F(6,114) = 7.28; P < 0.001), and IC total EE (F(6,114) = 7.28; P < 0.001). Although men had higher IC values than women at all speeds, the change in IC at lower speeds (54–134 m·min^{-1}) was similar for men and women. As speed increased to 161, 188, and 214 m·min^{-1}, the change in IC values was much greater for men than for women. There was also an interaction of gender and speed for TriTrac-R3D estimated activity EE (F(6,114) = 4.40; P < 0.001), TriTrac-R3D estimated total EE (F(6,114) = 4.40; P < 0.001), and SenseWear Armband estimated total EE (F(6,102) = 6.58; P < 0.001). Men had higher TriTrac-R3D estimated activity EE and total EE than women only during speeds 188 and 214 m·min^{-1} (P < 0.05). In contrast, Men had higher SenseWear estimates of total EE as compared with women at all speeds *except* 188 m·min^{-1} (P = 0.12).

Correlations. Correlations between measures of IC and each monitor indicator are shown in Table 3. For CSA indicators, the Freedson equation total calories provided the best estimate of EE. In general, correlations between CSA total EE estimated with the Freedson equation (9) and IC decreased as speed increased, from r = 0.73 at 54 m·min^{-1} to r = 0.58 at 214 m·min^{-1}. Between the BioTrainer-Pro activity EE and IC EE, correlations values improved from 54 m·min^{-1} (r = 0.34) to 107 m·min^{-1} (r = 0.61) but then

TABLE 3. Correlations among monitor indicators and indirect calorimetry (IC) measures for each speed.

	54 m·min^{-1}	80 m·min^{-1}	107 m·min^{-1}	134 m·min^{-1}	161 m·min^{-1}	188 m·min^{-1}	214 m·min^{-1}
IC activity EE							
CSA activity counts	−0.23	−0.15	0.19	−0.10	0.07	0.01	0.01
CSA total EE	0.06	0.35	0.52	0.44	0.57	0.54	0.55
Freedson total EE	0.53	0.63	0.57	0.48	0.56	0.55	0.57
BioTrainer activity EE	0.15	0.44	0.59	0.50	0.63	0.47	0.47
TriTrac vecmag	−0.46	−0.25	−0.25	0.11	0.34	0.29	0.18
TriTrac activity EE	0.06	0.38	0.34	0.64	0.75	0.82	0.81
TriTrac total EE	0.23	0.48	0.41	0.67	0.77	0.83	0.83
RT3 vecmag	−0.49	−0.34	−0.32	0.06	0.22	0.08	−0.02
RT3 activity EE	0.02	0.30	0.51	0.67	0.73	0.67	0.66
RT3 total EE	0.18	0.40	0.59	0.70	0.75	0.69	0.68
SW long axis	−0.37	0.04	−0.38	0.15	0.33	0.31	0.25
SW trans axis	−0.32	−0.66	−0.63	0.33	0.41	0.37	0.20
SW total EE	0.50	0.76	0.71	0.80	0.84	0.73	0.81
IC total EE							
CSA activity counts	−0.23	−0.16	0.13	−0.12	0.05	0.00	0.01
CSA total EE	0.14	0.41	0.56	0.45	0.56	0.54	0.56
Freedson total EE	0.73	0.72	0.64	0.49	0.56	0.55	0.58
BioTrainer activity EE	0.34	0.54	0.61	0.53	0.64	0.49	0.49
TriTrac vecmag	−0.30	−0.18	−0.29	0.09	0.33	0.28	0.17
TriTrac activity EE	0.31	0.50	0.40	0.66	0.76	0.83	0.81
TriTrac total EE	0.49	0.60	0.48	0.69	0.78	0.84	0.83
RT3 vecmag	−0.41	−0.29	−0.32	0.03	0.20	0.08	−0.04
RT3 activity EE	0.21	0.40	0.56	0.68	0.74	0.67	0.66
RT3 total EE	0.39	0.50	0.63	0.71	0.76	0.69	0.69
SW long axis	−0.47	−0.02	−0.45	0.12	0.31	0.29	0.24
SW trans axis	−0.20	−0.64	−0.70	0.31	0.40	0.36	0.20
SW total EE	0.65	0.82	0.75	0.81	0.85	0.73	0.82

Counts (accelerometric counts), vector magnitude (vecmag), energy expenditure (EE), Freedson EE (9), EE (kcal·min^{-1}), SenseWear Armband (SW).

began to decrease at 134 m·min^{-1} and were r = 0.485 at 214 m·min^{-1}.

Of all TriTrac-R3D indicators, the total EE values provided the best estimate of EE compared with IC. Correlations between TriTrac-R3D estimates of total EE and IC increased with increasing speed from 54 m·min^{-1} (r = 0.49) to 214 m·min^{-1} (r = 0.83). These findings were similar for the RT3, with total EE providing the best estimate of EE and a steady increase in correlations with IC from 54 m·min^{-1} (r = 0.39) to 214 m·min^{-1} (r = 0.685). In general, the RT3 correlations with IC were lower than those between the TriTrac-R3D and IC.

Finally, the correlations between the SenseWear Armband total EE estimates and IC EE were far better than either of the axis counts. SenseWear Armband and IC total EE were moderately correlated at 54 m·min^{-1} (r = 0.65), but correlations increased quickly at 80 m·min^{-1} to r = 0.82 and continued to stay high through 214 m·min^{-1} (r = 0.82).

DISCUSSION

The purpose of this study was to determine the validity of five physical activity monitors available for research: the CSA, TriTrac-R3D, RT3, BioTrainer-Pro, and SenseWear Armband. Validity was investigated by comparing EE estimates for each monitor to actual EE determined with IC. In general, all monitors overestimated EE at all speeds of walking and running, except for the CSA which underestimated EE when participants walked very slowly, jogged, and ran fast (Figs. 1 and 2), and the TriTrac-R3D which provided good estimates of total EE at the highest treadmill speed (Figs. 1 and 2). All monitors provided the same estimates of EE on left and right sides of the body. Our results are similar to those previously reported for the TriTrac-R3D (23,26,27), BioTrainer (25,26), and CSA (2,9,10). This study is the first known to evaluate the SenseWear and one of the first done with the RT3 (21).

Our findings suggest that the CSA is best for estimates of total EE at walking and jogging speeds, the TriTrac-R3D for estimates of total EE at running speeds, and the SenseWear Armband for estimates of total EE at most speeds (except for slow walking). Although not reflected in the correlations, it appears that activity and total EE estimated with the RT3 are the best reflection of changes in velocity for both men and women (see Figs. 1 and 2). This is apparent in the RT3's similar changes to IC with increased treadmill speed. The CSA and to some extent the BioTrainer-Pro, showed the poorest estimated EE responses to velocity in both men and women (see Figs. 1 and 2).

Differences were found between men and women in estimated monitor and actual EE changes with increases in treadmill speed. These differences are likely due to the fact that men have a greater mean body mass and quantity of lean tissue as compared with women, which corresponds to a greater energy cost of work during weight-bearing activity. The disparate pattern for men and women in the mag-

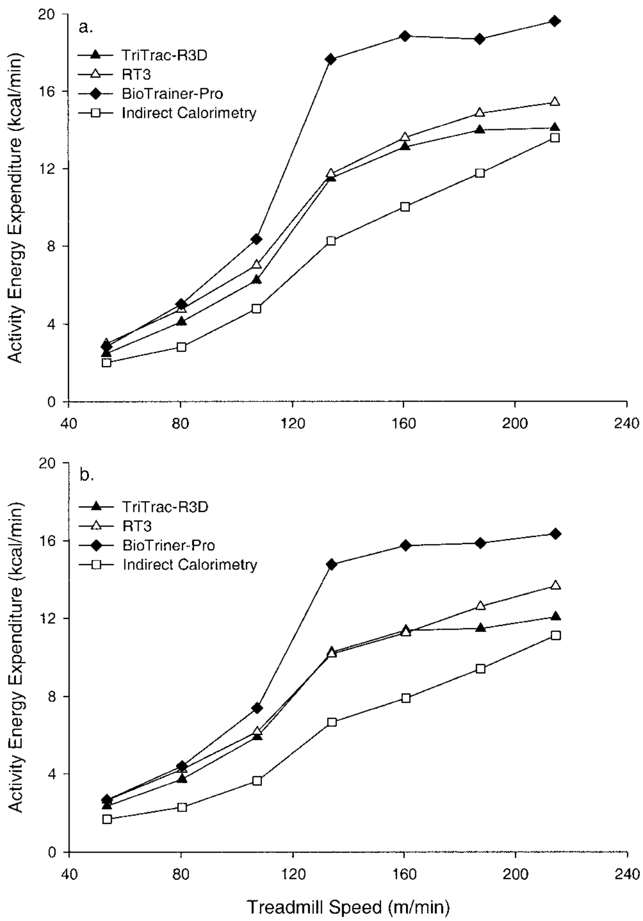

FIGURE 1—Average estimated activity energy expenditure (kcal·min^{-1}) in a) men and b) women for the TriTrac-R3D, RT3, and BioTrainer-Pro physical activity monitors across each treadmill speed. Actual activity energy expenditure is provided as a comparison. Treadmill speeds of 54, 80, 107, 134, 161, 188, and 214 m·min^{-1} corresponded to 2, 3, 4, 5, 6, 7, and 8 mph, respectively.

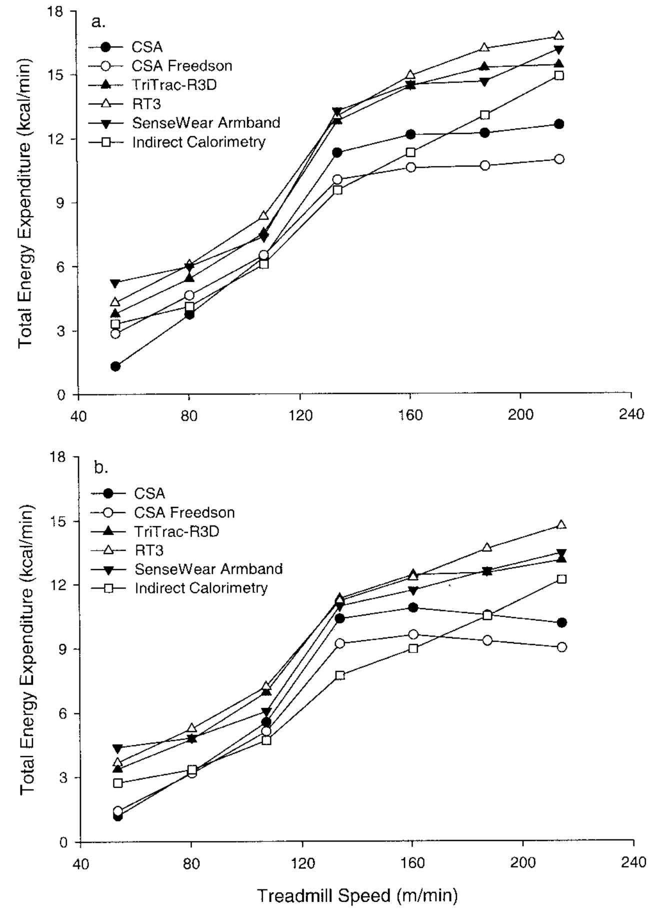

FIGURE 2—Average estimated total energy expenditure (kcal·min^{-1}) in a) men and b) women for the CSA, TriTrac-R3D, RT3, and SenseWear physical activity monitors across each treadmill speed. Actual total energy expenditure is provided as a comparison. Treadmill speeds of 54, 80, 107, 134, 161, 188, and 214 m·min^{-1} corresponded to 2, 3, 4, 5, 6, 7, and 8 mph, respectively.

nitude of change in estimated and actual EE values across treadmill speeds could be partially attributed to a difference in the mechanical efficiency of men and women or the decrease in mechanical efficiency associated with higher relative exercise intensity. The theoretical construct that acceleration increases in several dimensions with faster movements suggests that accelerometry based physical activity monitors may misinterpret the greater body movement associated with reduced mechanical efficiency. This has important implications for the validity of activity monitors for people with inefficient body movement during exercise such as those who are obese or with poor fitness as the monitors may overestimate energy expenditure due to excessive body motion.

Although correlations were not contrasted directly, they provide some evidence for which monitors are the best indicators of EE during weight bearing exercise such as walking and running. As Table 3 illustrates, the highest correlations at 54 and 80 m·min^{-1} were obtained with the CSA total EE estimated with the Freedson equation (9) and the SenseWear Armband total EE ($r = 0.65$–0.82). At speeds of 107, 134, and 161 m·min^{-1} the SenseWear Armband total EE was the closest indicator of EE ($r = 0.75$–0.85). For 188 m·min^{-1}, the TriTrac-R3D total EE was the closest estimate of EE ($r = 0.84$), and for 214 m·min^{-1}, it was also a good estimate of EE ($r = 0.83$) along with the SenseWear Armband total EE ($r = 0.82$). Of the three new monitors evaluated, the BioTrainer-Pro performed poorly across most speeds.

With the many recent health recommendations regarding moderate physical activity, the U.S. obesity epidemic, and the high prevalence of cardiovascular disease in the United States, the need for objective tools to monitor physical activity is evident. Motion sensors have a number of advantages over other forms of physical activity measurement (19). These small, unobtrusive devices have the capacity to store movement data for long periods of time, which eliminates many problems associated with the subjective recall of physical activity in questionnaires. Being objective measures of frequency, intensity, and duration make accelerometers ideal for answering questions regarding "patterns" of physical activity (4), which cannot be determined by other measures of EE, such as doubly labeled water or extended duration oxygen consumption.

General criticisms of belt-mounted physical activity monitors include the inability to detect arm movements, locomotion on a grade, and/or external work performed by pushing, lifting, or carrying objects (9,11,19). Although the RT3 and the BioTrainer-Pro remain subject to these criticisms, the SenseWear Armband may circumvent these issues by the incorporation of heat production measurements and placement on the upper arm.

A number of avenues remain for future research with these motion sensors. Foremost is the direct comparison between the RT3, BioTrainer-Pro, and SenseWear Armband during a variety of laboratory and field conditions, including cross-validation and free-living assessments. Although no single measurement device may prove to be the most effective method for objectively assessing physical activity, the further development of cost-effective motion sensing devices should focus on multi-parameter instruments for accurate data acquisition.

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Conflict of interest: No support was provided for this study by any manufacturer of the instruments used. Additionally, the results of the present study do not represent an endorsement of any product by the authors or the ACSM.

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