Evaluation of activity monitors in manual wheelchair users with paraplegia

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Objective: The aim of this study was to evaluate the performance of SenseWear® (SW) and RT3 activity monitors (AMs) in estimating energy expenditure (EE) in manual wheelchair users (MWUs) with paraplegia for a variety of physical activities.

Methods: Twenty-four subjects completed four activities including resting, wheelchair propulsion, arm-ergometry exercise, and deskwork. The criterion EE was measured by a K4b2 portable metabolic cart. The EE estimated by the SW and RT3 were compared with the criterion EE by the absolute differences and absolute percentage errors. Intraclass correlations and the Bland and Altman plots were also used to assess the agreements between the two AMs and the metabolic cart. Correlations between the criterion EE and the estimated EE and sensors data from the AMs were evaluated.

Results: The EE estimation errors for the AMs varied from 24.4 to 125.8% for the SW and from 22.0 to 52.8% for the RT3. The intraclass correlation coefficients (ICCs) between the criterion EE and the EE estimated by the two AMs for each activity and all activities as a whole were considered poor with all the ICCs smaller than 0.75. Except for deskwork, the EE from the SW was more correlated to the criterion EE than the EE from the RT3.

Conclusion: The results indicate that neither of the AMs is an appropriate tool for quantifying physical activity in MWUs with paraplegia. However, the accuracy of EE estimation could be potentially improved by building new regression models based on wheelchair-related activities.

Keywords: Spinal cord injuries, Paraplegia, Wheelchairs, Energy expenditure, Accelerometer, Wheelchair propulsion, Arm-ergometry test, Deskwork

Introduction

Lack of regular physical activity (PA) in the general population is a major public health concern, and this problem is even more acute among people with disabilities.¹ Healthy People 2010 indicates that people with disabilities in the United States have lower participation rates in regular physical activities compared to the general population.² Included among people with disabilities are persons with spinal cord injury (SCI) who are ranked on the lower end of the PA spectrum; with only 13–16% of persons with SCI having reported regular PA and the majority having reported virtually no regular PA.^{3–5} Low levels of PA in this population have been associated with decreased aerobic capacity, muscular strength and endurance, and flexibility, all of which have the potential for restricting their functional independence and increasing their risks for chronic diseases and secondary complications.^{6,7}

One of the strategies to promote regular PA is to obtain an accurate estimate of everyday PA, which could increase people's awareness of their own activity levels, promote PA adherence, and also allow researchers to determine the effectiveness of PA promotion programs.^{8,9} However, there are a limited number of PA measurement tools particularly designed for people with SCI, and almost all of them rely on self-reports.¹⁰ Although self-report measures are inexpensive and widely used, they are subject to recall bias, social desirability bias leading to over-reporting of PA, insensitivity to measure low-intensity activities, and inaccuracy to quantify PA intensity.¹⁰ Recent technological advances allow more objective and accurate measurements of free-living PA by sensor-based activity monitors (AMs). These AMs range from simple pedometers to more sophisticated motion-based devices such as the RT3 tri-axial accelerometer (Stayhealthy Inc., Monrovia, CA, USA) and the SenseWear® multi-sensor armband (BodyMedia Inc., Pittsburgh, PA, USA).^{11,12} Extensive studies have been performed to evaluate the validity and usefulness of AMs in

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measuring PA and predicting energy expenditure (EE) in ambulatory populations without disabilities.^{9,11,12} For example, St-Onge *et al.* evaluated the SenseWear[®] armband for measuring daily and PA EE in 45 healthy adults.¹³ They concluded that the armband showed reasonable concordance with doubly labeled water with an intraclass correlation of 0.81. Rothney *et al.* evaluated three AMs including ActiGraph, Actical, and RT3 accelerometers in 85 healthy adults.¹⁴ The measures of these devices were found to be not significantly different from those collected with the room calorimetry and showed differences of less than 2% in the moderate and vigorous intensity activities. However, very few studies have researched the performance of AMs to assess activity-related EE in people with SCI who often rely on wheelchairs as their primary means of mobility.^{3,15} As the AMs on the market are usually designed to capture lower extremity movement of the ambulatory population, they may not be able to accurately capture the types of physical movement that wheelchair users typically perform with their upper extremities.

A few studies have investigated the usefulness of AMs among wheelchair users with SCI. Washburn *et al.* investigated the validity of the CSA accelerometer (Computer Science and Applications Inc., Shalimar, FL, USA) with respect to the EE measured by an Aerosport TEEM 100 Total Metabolic Analysis System in 21 manual wheelchair users (MWUs) during wheelchair propulsion on an indoor track. The CSA accelerometers were worn on the wrists of the participants when they propelled their own wheelchairs at three different speeds. Significant correlations (0.52–0.66, $P < 0.01$) were reported between the activity counts from both wrists and EE over the three pushing speeds.³ Warms and Belza evaluated the validity of the accelerometry-based Actiwatch (ActiGraph Inc., Pensacola, FL, USA) to measure community living PA in 22 wheelchair users with SCI with respect to self-reported activity. The Pearson correlation coefficients between the activity counts and the self-reported activity intensity varied from 0.30 to 0.77 for individual participants.¹⁵ Researchers have also utilized wheel rotation dataloggers to assess PA in terms of distance traveled and speed of MWUs in the National Veterans Wheelchair Games and in the community settings.¹⁶ They found that the participants traveled a distance of 6745.3 ± 1937.9 m per day at a speed of 1.0 ± 0.2 m/second in the National Veterans Wheelchair Games, and a distance of 2457.0 ± 1195.7 m per day at a speed of 0.8 ± 0.2 m/second in the community settings. In general, the results from previous work indicate that

an AM worn on the upper limb has the potential to detect variability in activity-related EE among MWUs with SCI. However, it remains unknown to what extent the AMs worn at different body parts overestimate or underestimate the PA levels among this population.

The primary aim of this study was to evaluate the performance of the SenseWear[®] multi-sensor armband (denoted by SW hereafter) on the upper limb and the RT3 tri-axial accelerometer (denoted by RT3 hereafter) around the waist in estimating the EE in MWUs with paraplegia for resting and three types of physical activities including wheelchair propulsion, arm-ergometer exercise, and deskwork.

Methods

Subjects

The study was approved by the Institutional Review Board (IRB). The study was advertised via flyers and advertisements in print media (e.g. magazines, newspapers, and newsletters) and web-based postings. Flyers were also mailed to potential participants who were part of the IRB-approved wheelchair user registries.¹⁷ Interested participants were screened by the investigators using a screening script. Subjects were recruited based on the inclusion criteria that they were between 18 and 60 years of age, used a manual wheelchair as a primary means of mobility, have an SCI of T1 or below (i.e. paraplegia), were at least 6 months post-injury, were free of cardiovascular and respiratory diseases, and were able to use an arm-ergometer to exercise. Subjects were excluded if they were unable to tolerate sitting for 4 hours, had active pelvic or thigh wounds, or failed to obtain physician consent to participate from their primary care physician. As part of the study, subjects were asked to refrain from consuming food, caffeine, and tobacco products for at least 2 hours, and avoid exercising at least 12 hours prior to their arrival at the laboratory. All subjects provided written informed consent prior to their participation in this study.

Instrumentation

Two AMs including the SW and RT3 were used. The SW consists of a unique array of biometric sensors including a three-axis accelerometer, a skin temperature sensor, a Galvanic Skin Response sensor, and a near-body temperature sensor. The SW analysis software (InnerView Research Software 7.0) uses sensor data, height, weight, age, gender, dominant hand, and smoking status of the subjects to estimate the EE for resting and different types of PAs. As per the

manufacturer's instructions, the SW was worn on the right upper arm over the triceps muscle (Fig. 1). The RT3 consists of a piezoelectric tri-axial accelerometer. Its software (RT3 ASSIST) converts the raw acceleration data into activity counts based on proprietary equations. The software uses activity counts, height, weight, age, and gender of the subjects to estimate resting and activity EE. As per the manufacturer's instructions, the RT3 was secured around the waist as shown in Fig. 1 with a belt-clip holster. In addition, subjects also wore a portable metabolic cart K4b2 (COSMED srl, Rome, Italy) and a Polar T31 heart rate monitor (Polar Electro Inc., Lake Success, NY, USA). The K4b2 metabolic cart comprises of an analyzer unit (about 1.5 kg with the battery) and a rubber face mask covering the participant's mouth and nose. The analyzer unit was placed on the chest with the battery pack on the back and the face mask was held in place with a head cap (Fig. 1). The exhaled air is channeled through a ventilation turbine into the analyzer unit where the quantities of O₂ and CO₂ in the expired air are measured. The K4b2 has been shown to be both reliable and valid in the general population,^{18,19} and has been used to measure EE and oxygen consumption in published studies involving persons with SCI.^{20,21} The system was calibrated for every subject before use to ensure its accuracy. Cosmed 9.0 software was used to retrieve and analyze the metabolic data. The Polar T31 heart rate monitor was firmly secured on the chest using an elastic strap. The heart rate transmitted by the Polar T31 was captured by a wireless receiver module connected to the K4b2.

Figure 1 The SenseWear® and the RT3 tri-axial accelerometer worn by a study participant.

Experimental protocol

The protocol started with a pre-activity session where subjects answered a questionnaire including questions on demographics, wheelchair information, and health and PA history. Body weight was then measured using a Befour MX490D extra wide wheelchair scale (Befour, Inc., Saukville, WI, USA) to the nearest 0.5 kg. Each subjects' height was either self-reported or measured by taking the sum of the sitting height, sitting depth, and lower leg length²² using a Stanley® Tape Rule (The Stanley Works, New Britain, CT, USA) to the nearest 0.1 cm. Skinfold measurements were carried out at biceps, triceps, subscapular, and suprailiac using a Lange® skinfold caliper (Beta Technology, Santa Cruz, CA, USA) to the nearest millimeter. The body fat percentage was obtained through the lookup tables included in the Lange skinfold manual based on the sum of skinfold measurements, age, and gender.²³

The activity session consisted of resting and three activity routines including wheelchair propulsion, arm-ergometer exercise, and deskwork. During the resting routine, subjects were required to be seated quietly in their wheelchairs for a period of 8 minutes while the metabolic cart and the AMs were used to collect EE. The wheelchair propulsion routine included three trials, i.e. 0.89 m/s (2 mph) and 1.34 m/s (3 mph) on a computer-controlled dynamometer and 1.34 m/s (3 mph) on a flat tiled surface. The propulsion speed on the dynamometer was regulated by providing feedback through a monitor in front of the subjects. On the tiled surface, subjects were required to follow a powered wheelchair set at a fixed speed of 1.34 m/s (3 mph). The arm-ergometer exercise routine included three trials, i.e. 20 watts (W) resistance at 60 rotations per minute (rpm), 40 W at 60 rpm, and 40 W at 90 rpm on an Angio arm-ergometer with an automatic stand (Lode B.V., Groningen, The Netherlands). During the deskwork routine, subjects were asked to retrieve a set of books from a table and pick one to read for 4 minutes, and type on a computer for 4 minutes using a typing test computer program. The activity routines were counterbalanced and the trials within each activity routine were randomized to counter order and carry-over effects. Subjects were given at least 2 minutes practice prior to each activity trial. They were asked to perform each activity trial for 8 minutes. Subjects were provided with a resting period of 5–10 minutes between each trial and a resting period of 30–40 minutes between each activity routine. Subjects completed only those trials that they

were comfortable to perform. They were also asked to provide a rating of perceived exertion on the Borg categorical ratio scale (CR-10) after each trial.²⁴

Data collection and analysis

The K4b2 metabolic cart, SW and RT3 were synchronized before use. The data collected from the K4b2 included volume of oxygen (VO_2) and volume of carbon dioxide (VCO_2) in ml/minute/kg, heart rate, metabolic equivalent of tasks (MET) using a reference of 3.5 ml/minute/kg, and EE in kcal/minute for each breath. We also calculated MET based on previous research on people with SCI (MET-SCI) by using a reference metabolic rate of 2.7 ml/minute/kg for the SCI population.²⁵ The data collected from the SW included the average resultant acceleration and the mean absolute deviation in longitudinal and transverse accelerations at 16 Hz and skin temperature, galvanic skin response, near-body temperature, and EE in kcal/minute at each minute. The data collected from the RT3 included the resultant activity counts and EE in kcal/minute at 1 Hz. The data analysis software was written in MATLAB® (Version 7.6 R2008a, The Mathworks Inc., Natick, MA, USA) and used to process and analyze data from the metabolic cart and the AMs. To determine steady-state or near-steady-state conditions, EE data in kcal/minute for each activity trial were obtained by first averaging breath-by-breath measures over 30-second periods.²⁵ EE values having coefficients of variation of less than 10% computed over windows of at least 1 minute were then averaged and used in later analyses.²⁶

Comparisons between the criterion EE from the K4b2 metabolic cart and the estimated EE from the two AMs were performed by calculating the absolute differences and absolute percentage errors, and plotting the mean differences for each activity trial. Intraclass correlation coefficients (ICC(3,1)) for a single measure using the two-way mixed model with consistency were used to assess the agreement between the criterion EE and the EE estimated by the AMs. An ICC value of 0.9 is deemed excellent if the lower bounds are greater than or equal to 0.75.²⁷ The Bland and Altman plots were used to assess the agreement between the criterion EE and the EE estimated by the AMs.²⁸ Each point on the Bland and Altman plot represents the mean (x -axis) and the difference (y -axis) of the criterion EE and the estimated EE for each activity trial of each subject. The agreement between the criterion EE and the estimated EE from the AMs were evaluated based on the bandwidth of the plots (mean $\pm$ 2SD). Shapiro–Wilk’s test was performed to determine whether

the data were normally distributed. Non-parametric analysis was chosen as all the variables were not normally distributed. Spearman’s rho were computed between the criterion EE and the SW outputs including the EE, the average resultant acceleration, the mean absolute deviation in longitudinal and transverse accelerations, the skin temperature sensor, the galvanic skin response sensor, and the near-body temperature sensor. Spearman’s rho were also computed between the criterion EE and the RT3 outputs including the EE and the resultant activity count. All statistical analyses were performed using SPSS software (ver. 15.0, SPSS Inc., Chicago, IL, USA), with the statistical significance at an alpha level of 0.05.

Results

A total of 24 MWUs with paraplegia participated in the study. The number of subjects was determined based on a power analysis using a paired t -test with an alpha level of 0.05, effect size of 0.6, and power of 80%. A medium to large effect size range was chosen due to the fact the AMs were not designed for our target population and thus were not expected to accurately estimate the EE of wheelchair-related activities. There were 19 males and 5 females with a mean age of 41.4 ± 11.4 years, weight of 82.4 ± 25.1 kg, height of 178.0 ± 9.4 cm, and body fat percentage of $28.0 \pm 7.3\%$. The injury level of the subjects varied from T3 to L4, with 9 subjects having injuries above T6, 12 subjects having injuries between T7 and T12, and 3 subjects having injuries between L1 and L4. Eleven of the 24 subjects had a complete injury. The number of years subjects have used a manual wheelchair was 12.8 ± 8.0 . Self-reported PA indicated that 10 subjects performed regular PA; 8 performed occasional PA; and 6 performed no regular PA. The top three common PAs reported were wheelchair basketball, weight lifting, and arm-ergometry. Perceived fitness level among the subjects varied from excellent to poor with 18 subjects reporting at least good fitness level, 5 reporting fair fitness level, and 1 reporting poor fitness level. Eighteen of the 24 subjects reported themselves to be non-smokers.

All the 24 subjects in the study completed the eight activity trials. Most of these activity trials (176 out of 192 trials) were performed for 8 minutes as requested, whereas 16 trials were between 4 and 8 minutes. Among the 192 trials, three trials including one resting trial, one 2 mph propulsion trial on a dynamometer, and one deskwork trial that did not yield steady-state or near steady-state conditions were discarded. Due to device malfunction of the K4b2, two trials including one 3 mph propulsion trial on the tiled surface and

one resting trial were also discarded. In addition, the RT3 data from the eighth participant were lost due to device malfunction. The metabolic costs in kcal/minute from the K4b2 metabolic cart, the EE estimated by the SW and the RT3, the MET from the metabolic cart, the MET-SCI, the heart rate (beats/minute), the rating of perceived exertion, and the number of subjects who completed each activity trial are shown in Table 1. The EE, heart rate, and rating of perceived exertion for propulsion and arm-ergometry exercises increased with the increase in speed and resistance. Utilizing the MET-SCI as a reference, the wheelchair propulsion trials on the dynamometer and arm-ergometry exercise trials were considered as moderate intensity activities (MET-SCI between 3.0 and 6.0), whereas the resting, 3 mph wheelchair propulsion on the tiled surface and deskwork were light intensity activities (MET-SCI < 3.0).²⁹

Table 2 shows the absolute differences and absolute percentage errors between the criterion EE and the estimated EE from the AMs. The absolute rather than average values were reported, as the AMs, especially the RT3, overestimated EE for some subjects but underestimated EE for others. Fig. 2 further illustrates the differences between the criterion EE and the estimated EE by displaying the mean difference and its 95% confidence intervals ($\pm 2SD$) for each PA. The 95% confidence intervals for deskwork and resting trials were much smaller compared to wheelchair propulsion and arm-ergometry exercise trials. The agreements between the criterion EE and the estimated EE from the two AMs were also evaluated by the ICCs (Table 3) and the Bland and Altman plots (Fig. 3). The Spearman rho correlations between the criterion EE and the estimated EE and raw sensor outputs from the SW and the RT3 AMs are shown in Table 4.

Discussion

AMs have been extensively studied to measure PA and predict activity-related EE among the ambulatory

Table 2 Difference between the EE from the metabolic cart and EE outputs from the SW and the RT3

Activity mean (SD)	Absolute difference (kcal/minute)		Absolute percentage error (%)	
	SW	RT3	SW	RT3
Resting	0.2 (0.2)	0.3 (0.2)	24.7 (19.4)	30.4 (18.9)
2 mph on dyno	4.7 (3.8)	1.3 (1.9)	130.0 (96.1)	33.8 (35.2)
3 mph on dyno	4.2 (3.9)	1.9 (2.9)	95.2 (71.7)	32.3 (31.8)
3 mph on tile	3.2 (1.4)	1.2 (1.6)	114.8 (61.8)	39.2 (34.2)
20 W at 60 rpm	2.1 (1.1)	1.3 (0.9)	66.2 (34.8)	41.3 (11.9)
40 W at 60 rpm	1.6 (1.1)	2.1 (1.3)	38.2 (29.6)	46.9 (20.1)
40 W at 90 rpm	2.3 (1.5)	2.4 (2.0)	40.4 (24.1)	43.1 (19.1)
Deskwork	0.3 (0.1)	0.2 (0.3)	20.1 (14.0)	17.0 (10.3)

Figure 2 Plots of the difference between the criterion EE and the EE from the AMs for each PA.

population without disabilities.^{9,11,12} However, very few studies have evaluated AMs among wheelchair users.^{3,15} Given the high prevalence of physical inactivity in this population, the availability of a reliable and

Table 1 Metabolic costs, heart rate, rate of perceived exertion, and number of subjects per trial for four types of physical activities

Activity mean (SD)	EE (kcal/minute)			MET K4b2	MET-SCI	Heart rate (beats/minute)	RPE	Number of subjects
	K4b2	SW	RT3					
Resting	1.1 (0.3)	1.3 (0.3)	1.4 (0.3)	0.8 (0.2)	1.1 (0.2)	71.6 (10.6)	0.0 (0.0)	22
2 mph on dyno	3.7 (1.5)	7.9 (4.2)	3.9 (2.2)	2.7 (0.8)	3.5 (1.0)	105.5 (16.0)	3.2 (1.6)	23
3 mph on dyno	4.7 (2.1)	9.0 (4.3)	5.6 (3.8)	3.4 (1.2)	4.4 (1.6)	118.2 (25.2)	4.8 (2.4)	24
3 mph on tile	2.9 (1.1)	6.1 (1.9)	3.6 (1.9)	2.1 (0.5)	2.7 (0.6)	94.4 (20.1)	2.4 (1.4)	23
20 W at 60 rpm	3.1 (0.5)	5.6 (1.9)	2.9 (1.9)	2.4 (0.4)	3.1 (0.6)	103.1 (15.3)	1.9 (1.7)	24
40 W at 60 rpm	4.4 (0.6)	6.2 (1.9)	3.3 (2.0)	3.4 (0.8)	4.4 (1.0)	119.0 (18.6)	3.4 (2.5)	24
40 W at 90 rpm	5.5 (1.0)	8.3 (3.2)	5.4 (3.6)	4.0 (0.6)	5.2 (0.8)	138.3 (19.7)	5.3 (2.9)	24
Deskwork	1.3 (0.4)	1.6 (0.3)	1.4 (0.4)	1.0 (0.2)	1.3 (0.3)	85.1 (16.1)	0.4 (0.5)	23

Table 3 Intraclass correlations ICC(3,1) between the EE measured by the metabolic cart (K4b2) and the EE estimated by the SW and the RT3

Activity	ICC(3,1) k4b2 – SW			ICC(3,1) k4b2 – RT3		
	ICC	LB	UB	ICC	LB	UB
Resting	0.61*	0.16	0.85	0.53*	0.02	0.82
Propulsion	0.47*	0.21	0.67	0.52*	0.26	0.70
Arm-ergometry	0.64*	0.43	0.79	0.40*	0.12	0.62
Deskwork	0.61*	0.17	0.85	0.60*	0.12	0.85
All Activities	0.62*	0.49	0.72	0.64*	0.51	0.73

'LB' is the lower bound and 'UB' is the upper bound.

*Correlations that were significant with $P < 0.05$.

Figure 3 The Bland and Altman plots of the EE from the metabolic cart (K4b2) versus the EE from the SW and the RT3 for all activity trials.

valid AM is even more critical in assisting these individuals to understand and self-manage their PA behaviors.^{3–5} In this study, we evaluated the performance of two commercially available AMs in predicting EE among MWUs with paraplegia. Previous studies only looked into the correlations between one-axis

accelerometer recordings and EE from a metabolic cart³ during wheelchair propulsion or between one-axis accelerometer recordings and self-reported PA intensity.¹⁵ This study evaluated two state-of-the-art AMs with a more comprehensive protocol. The study will also inform the amount of errors when using the two AMs among MWUs with paraplegia. The findings of this study will provide insights into designing a new AM or modifying the existing ones specifically for this population.

Unlike the previous studies that found small differences between the EE estimated by the AMs and the criterion EE measured by the metabolic cart among the ambulatory population,^{9,11,12} our study discovered relatively large discrepancies in EE estimation by the two AMs among wheelchair users with paraplegia. The estimation errors ranged from 24.4 to 125.8% for the SW and from 22.0 to 52.8% for the RT3. The results indicated that neither of the two AMs is appropriate for self-monitoring EE estimation and PA levels in wheelchair users with paraplegia. A close examination of the EE estimation errors for light intensity PAs such as resting and deskwork revealed relatively small differences (0.3–0.4 kcal/minute) (Table 2). The small EE differences could be due to the fact that user characteristics such as body weight, height, gender, and age play a greater role in the EE predictive equations than body movements during PAs of light intensities.^{9,11,12,30} In terms of wheelchair propulsion and arm-ergometry, the EE estimation errors were greater for the SW compared to the RT3. As shown in Figs. 2 and 3, the SW significantly overestimated EE for wheelchair propulsion and arm-ergometry. The overestimation of EE using the SW could be that the current algorithms present in the SW were developed and refined exclusively among the ambulatory population. Instead of using a single EE prediction equation for all types of PAs as other AMs do, the SW first classifies an activity into a predefined category and then uses the activity-specific

Table 4 Spearman rho correlations between the criterion EE (K4b2) and the data from the SW and the data from the RT3

Activity	SW							RT3	
	EE	RAVG	LMAD	TMAD	STEMP	NTEMP	GSR	EE	RESAC
Resting	0.69*	0.47	−0.04	0.09	−0.11	0.20	0.63*	0.53	−0.01
Propulsion	0.76*	0.46*	0.75*	0.67*	0.27	−0.17	0.11	0.44*	0.31*
Arm-ergometry	0.69*	0.16	0.63*	0.63*	0.32*	−0.02	0.21	0.52*	0.40*
Deskwork	0.65*	0.17	0.22	−0.31	0.18	0.41	0.62*	0.66*	0.38
All Activities	0.84*	0.25*	0.77*	0.72*	0.54	0.07	0.09	0.72*	0.67*

*Correlations that were significant with $P < 0.05$.

RAVG: resultant average acceleration; LMAD: mean absolute deviation in longitudinal acceleration; TMAD: mean absolute deviation in transverse acceleration; STEMP: skin temperature; NTEMP: near-body temperature; GSR: galvanic skin response; RESAC: resultant acceleration count.

equation to estimate EE.⁹ Although the SW worn on the upper arm has the potential to capture the physical movements of the upper extremities, wheelchair propulsion and arm-ergometry were not included in the predefined activity categories in the SW; thus they were likely misclassified into a more strenuous type of PA leading to the overestimation of EE. The EE estimations from the RT3 during wheelchair propulsion and arm-ergometry were closer to the criterion EE than those from the SW, but the absolute percent errors were still over 40% for all the propulsion and arm-ergometry trials. When examining the estimation errors on an individual basis (Figs. 2 and 3), it was noted that the RT3 overestimated EE for some subjects but underestimated EE for others, indicating that subjects may propel their wheelchairs and perform arm-ergometry exercise in different styles, leading to different levels of trunk movements sensed by the RT3 around the waist.

In addition to the absolute differences and percentage errors, the ICCs between the criterion EE and the EE estimated by the two AMs for each activity trial and all activities as a whole were below 0.75 and considered poor (Table 3).²⁷ The Bland and Altman plots (Fig. 3) also showed a high bandwidth, greater than 1 kcal/minute, of EE estimation errors for both AMs, confirming that neither of the AMs should be used as an appropriate EE measurement tool for MWUs with paraplegia.^{18,19}

When examining the Spearman rho correlations shown in Table 4, we found that the physiological signals from the SW were not correlated well with the criterion EE. These physiological signals might be used to classify the types of PAs in the SW rather than predicting EE. It was also noted that the correlations of the acceleration features such as the mean absolute deviation in longitudinal and transverse accelerations produced by the SW with the criterion EE were higher than the correlations of the acceleration counts produced by the RT3 with the criterion EE. This indicates that the SW with appropriate modifications could potentially yield better EE prediction accuracy than the RT3. One possible reason for the greater correlations between the criterion EE and the SW outputs could be the different ways that raw acceleration signals were processed in the SW and RT3. The SW used feature extraction schemes to reduce raw acceleration signals sampled at 32 Hz to a small number of simple-to-compute statistical features. On the other hand, the RT3 first converted the raw acceleration signals into the activity counts at 1 Hz using a proprietary threshold-based method, and then produced time-integrated activity counts on a minute-by-minute basis. This simplified

data acquisition and analysis technique could potentially discard a large amount of useful information in raw acceleration signals by utilizing only integrated signals over 1-minute intervals. Previous studies on EE estimation using AMs among the ambulatory population have shown that the EE prediction accuracy could be improved using features of the raw acceleration signals compared to models using integrated signals.³¹ Another possible reason for the greater correlations between the criterion EE and the SW outputs could be the location of the AM. Although it is intuitive that the SW worn on the upper limb could better capture the upper limb movements in MWUs, the study design of placing two distinctly different devices (i.e. SW and RT3) at two different body locations (i.e. upper arm and waist) did not allow us to determine whether the devices themselves or the locations are more important for better prediction accuracy.

There are several limitations of the study including limiting the study to MWUs with paraplegia, small sample size, limited types of PAs in the protocol, and self-reported value of body height. The study chose to recruit only MWUs with paraplegia as an initial step in order to minimize the impact of different types and levels of disabilities on EE measurements. However, the methodology in this study could be used to test MWUs with other diagnoses. In terms of the sample size, the post hoc power analysis confirmed the large effect sizes (>0.6) for all trials using the SW and for two trials using the RT3 (i.e. resting and 40 W at 60 rpm arm-ergometry). However, the effect sizes for the other trials using the RT3 were smaller than what we used in the prior power analysis, indicating that more subjects will be needed to statistically detect the differences between the estimated EE and the criterion EE for these trials. In addition, two of the three propulsion trials over the dynamometer may not be representative of over ground propulsion in daily life. Lastly, the study design did not allow us to determine the best location for placing the AMs.

Future work will involve recruiting more subjects for developing new regression models of EE prediction for MWUs with paraplegia. Recommendations for future studies include evaluating AMs in MWUs with other diagnoses, testing more types PAs, and evaluating the effect of the number and location of AMs on the EE prediction accuracy for MWUs.

Conclusions

To our knowledge, this is the first study to evaluate the performance of commercially available AMs including the SW and RT3 in MWUs with paraplegia. The two

AMs were able to predict EE with relatively small errors during PAs of light intensity such as resting and desk-work, but did not estimate EE accurately during wheelchair propulsion and arm-ergometry. The RT3 in general had better performance in predicting EE during wheelchair propulsion and arm-ergometry exercise than the SW. However, the SW outputs had greater correlations with the criterion EE, indicating that the SW with appropriate regression models could potentially yield better EE prediction accuracy.

Acknowledgments

The present work was supported by RERC on Recreational Technologies and Exercise Physiology Benefitting Persons with Disabilities (H133E070029) funded by National Institute on Disability Rehabilitation Research (NIDRR). The work was also supported by VA Center of Excellence for Wheelchairs and Associated Rehabilitation Engineering B3142C. The contents of this paper do not represent the views of the Department of Veterans Affairs or the United States Government.

References

- Martin SB, Morrow JR, Jackson AW, Dunn AL. Variables related to meeting the CDC/ACSM physical activity guidelines. *Med Sci Sports Exerc* 2000;32(12):2087–92.
- U.S. Department of Health and Human Services. Healthy people 2010: understanding and improving health. Washington, DC: US Department of Health and Human Services; 2000. p. 26–7.
- Washburn RA, Copay AG. Assessing physical activity during wheelchair pushing: validity of a portable accelerometer. *Adapted Phys Activity Q* 1999;16(3):290–9.
- Fernhall B, Heffernan K, Jae SY, Hedrick B. Health implications of physical activity in individuals with spinal cord injury: a literature review. *J Health Hum Serv Adm* 2008;30(4):468–502.
- Washburn R, Hedrick BN. Descriptive epidemiology of physical activity in university graduates with locomotor disabilities. *Int J Rehabil Res* 1997;20(3):275–87.
- Glaser RM, Janssen TWJ, Suryaprasad AG, Gupta SC, Mathews T. The physiology of exercise. In: Apple DF (ed.) *Physical fitness: a guide for individuals with spinal cord injury*. Washington, DC: Department of Veterans Affairs; 1996. p. 1–24.
- Tawashy AE, Eng JJ, Lin KH, Tang PF, Hung C. Physical activity is related to lower levels of pain, fatigue and depression in individuals with spinal-cord injury: a correlational study. *Spinal Cord* 2009;47(7):301–6.
- Ainslie PN, Reilly T, Westerterp KR. Estimating human energy expenditure: a review of techniques with particular reference to doubly labelled water. *Sports Med* 2003;33(9):683–98.
- Andre D, Wolf DL. Recent advances in free-living physical activity monitoring: a review. *J Diabetes Sci Technol* 2007;1(5):760–7.
- Warms C. Physical activity measurement in persons with chronic and disabling conditions. *Fam Commun Health* 2006;29(Suppl 1):78S–88S.
- Jakicic JM, Marcus M, Gallagher K, Randall C. Evaluation of the SenseWear Pro armband to assess energy expenditure during exercise. *Med Sci Sports Exerc* 2004;36(5):897–904.
- Jacobi D, Perrin A-E, Grosman N, Doré M-F, Normand S, Oppert J-M, *et al.* Physical activity-related energy expenditure with the RT3 and tritrac accelerometers in overweight adults. *Obesity* 2007;15(4):950–6.
- St-Onge M, Mignault D, Allison D, Rabasa-Lhoret R. Evaluation of a portable device to measure daily energy expenditure in free-living adults. *Am J Clin Nutr* 2007;85(3):742–9.
- Rothney MP, Schaefer EV, Neumann MM, Choi L, Chen KY. Validity of physical activity intensity predictions by ActiGraph, Actical, and RT3 accelerometers. *Obesity* 2008;16(8):1946–52.
- Warms CA, Belza BL. Actigraphy as a measure of physical activity for wheelchair users with spinal cord injury. *Nurs Res* 2004;53(2):136–43.
- Tolerico ML, Ding D, Cooper RA, Spaeth DM, Fitzgerald SG, Cooper R, *et al.* Assessing mobility characteristics and activity levels of manual wheelchair users. *J Rehabil Res Dv* 2007;44(4):561–72.
- Fitzgerald SG, Kelleher A, Teodorski E, Collins DM, Boninger M, Cooper RA. The development of a nationwide registry of wheelchair users. *Disabil Rehabil: Assistive Technol* 2007;2(6):358–65.
- Duffield R, Dawson B, Pinnington HC, Wong P. Accuracy and reliability of a Cosmed K4 b2 portable gas analysis system. *J Sci Med Sport* 2004;7(1):11–22.
- McLaughlin JE, King GA, Howley ET, Bassett DR Jr, Ainsworth BE. Validation of the COSMED K4 b2 portable metabolic system. *Int J Sports Med* 2001;22(4):280–4.
- Abel T, Platen P, Vega SR, Schneider S, Struder HK. Energy expenditure in ball games for wheelchair users. *Spinal Cord* 2008;46(12):785–90.
- Kawashima N, Sone Y, Nakazawa K, Akai M, Yano H. Energy expenditure during walking with weight-bearing control (WBC) orthosis in thoracic level of paraplegic patients. *Spinal Cord* 2003;41(9):506–10.
- Cooper RA, Boninger ML, Cooper R, Thorman T. Wheelchairs and seating. In: Lin VW (ed.) *Spinal cord medicine: principle and practice*. New York, NY: Demos Medical Publishing; 2003. p. 635–55.
- Beta Technology, Inc. Lange Skinfold Caliper: Operators Manual. Beta Technology Website. [accessed 2007 Sept 1]. Available from: <http://www.beta-technology.com/documents/Caliper/080514%20Caliper%20Manual.pdf>.
- Borg G. Psychophysical scaling with applications in physical work and the perception of exertion. *Scand J Work Environ Health* 1990;16(Suppl 1):55–8.
- Collins EG, Gater D, Kiratli J, Butler J, Hanson K, Langbein WE. Energy cost of physical activities in persons with spinal cord injury. *Med Sci Sports Exerc* 2010;42(4):691–700.
- Starling RD. Use of doubly labeled water and indirect calorimetry to assess physical activity. In: Welk GJ (ed.) *Physical activity assessments for health-related research*. Champaign, IL: Human Kinetics; 2002. p. 197–209.
- Lee J, Koh D, Ong CN. Statistical evaluation of agreement between two methods for measuring the same quantity. *Comput Biol Med* 1989;19(1):61–70.
- Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet* 1986;1:307–10.
- Pate RR, Pratt M, Blair SN, Haskell WL, Macera CA, Bouchard C, *et al.* Physical activity and public health. A recommendation from the Centers for Disease Control and Prevention and the American College of Sports Medicine. *JAMA* 1995;273(5):402–7.
- Buchholz AC, Pencharz PB. Energy expenditure in chronic spinal cord injury. *Clinical Nutrition and Metabolic Care* 2004;7(6):635–9.
- Rothney MP. Advancing accelerometry-based physical activity monitors: quantifying measurement error and improving energy expenditure prediction [Dissertation]. Nashville, TN: Vanderbilt University; 2007. p. 91.