31st Annual International Conference of the IEEE EMBS
Minneapolis, Minnesota, USA, September 2-6, 2009

Evaluation of Activity Monitors to Estimate Energy Expenditure in Manual Wheelchair Users

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Abstract— **In an effort to make activity monitors usable by manual wheelchair users with Spinal Cord Injury (SCI), our study examines the validity of SenseWear® Armband (SenseWear) and RT3 in assessing energy expenditure (EE) during wheelchair related activities. This paper presents the data obtained from six subjects (n=6) with SCI performing three activities, including wheelchair propulsion, arm-ergometer exercise and deskwork. The analysis presented here compares the EE estimated from the SenseWear and the RT3 with respect to the EE measured from a portable metabolic cart. It was found that the SenseWear overestimated EE for resting (+5.78%), wheelchair propulsion (+88.20%, +46.20%, and +138.21% for the three trials at different intensities, respectively), arm-ergometer exercise (+55.05%, +26.91%, and +39.17% for the three trials at different intensities, respectively) and deskwork (+13.11%). The results also indicate that RT3 underestimated EE for resting (-3.06%), wheelchair propulsion (-24.23%, -19.42%, and -9.98% for the three trials at different intensities, respectively), arm-ergometer exercise (-49.06%, -53.69% and -52.08 for the three trials at different intensities, respectively) and measured EE relatively accurate for deskwork. Good and moderate Intraclass correlations were found between EE measured by metabolic cart and EE estimated by SenseWear (0.787, p<0.0001) and RT3 (0.705, p<0.0001). Weka, machine learning software, was used to select attributes and model EE equations for the SenseWear and the RT3. Excellent and good Intraclass correlations were found between the EE measured by the metabolic cart and the estimated EE based on the models for SenseWear (0.944, p<0.0001) and RT3 (0.821, p<0.0001). Future work will test more subjects to refine the model and provide manual wheelchair users with a valid tool to gauge their daily physical activity and EE.**

I. Introduction

The ease of using activity monitors and pedometers has motivated many segments of population to use them in their daily lives to know the amount of physical activity performed, energy expended or steps walked in a day [1], [2]. Regular self-monitoring in the free-living environment can help people provide important feedback towards a healthy lifestyle [3]. In ambulatory populations activities like walking and running, which involve weight bearing, account for a large portion of EE [4]. However, wheelchair users who are sedentary mainly utilize their upper body for all voluntary activities of daily living and exercise such as arm cranking and wheelchair propulsion [5]. Quantification of upper-extremity movement can provide us an adequate measure of physical activity among wheelchair users [5].

One of the research methods utilized widely to record and measure physical activities are self-reports. Self-report measures are inexpensive and easy to implement. However, the data may suffer from subject bias, inaccuracy from recall activities, and choice of consistent low or high score on the surveys leading to floor effects [6]. These difficulties in measurement and quantification of EE and physical activity can be averted by using activity monitors (AM). Activity monitors currently available in the market may range from mechanical pedometers to multi-sensor based wearable armbands [3].

Accelerometry-based AM have been studied and developed to measure activities and predict EE in ambulatory populations [1]-[3], [7]-[11]. The existing EE predictive equations have not considered the effect of chronic diseases and disabilities such as SCI [1], [2]. Washburn and Copay have assessed the validity of uniaxial accelerometers worn on the wrists as a measure of EE during wheelchair propulsion at three different speeds [12]. Significant associations were reported between the accelerometer readings from both wrists and EE over the three pushing speeds. Warms and Belza assessed the suitability and validity of a uniaxial accelerometer as a measure of community living physical activity for wheelchairs users with SCI [13]. The Pearson correlation coefficients between the activity counts and self-reported activity intensity varied from 0.30 to 0.77 for individual participants. However, research involving wheelchair users utilizing multi-sensor or multi-axis accelerometer based activity monitors to estimate EE is lacking.

In this paper we present the data obtained from six subjects (n=6) with SCI performing three physical activities, including wheelchair propulsion, arm-ergometer exercise and deskwork. The primary aim of the study is to examine the validity of SenseWear, a multi-sensor based AM, and RT3, a tri-axial accelerometer based AM, in assessing EE in manual wheelchair users during wheelchair related activities. The two devices are compared to a portable metabolic cart (indirect calorimetry), used as the criterion measure [14]. The secondary aim is to obtain statistical correlations between the EE from the metabolic cart and the estimated EE from the SenseWear and the RT3 AM. Based on the correlations, EE estimation models were developed for

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SenseWear and RT3 AM.

II. METHODOLOGY

A. Instrumentation

Two commercially available AM including a multi-sensor based SenseWear armband (Bodymedia Inc., Pittsburgh, PA [www.bodymedia.com]) and a triaxial accelerometer RT3 (Stayhealthy Inc., Monrovia, CA [www.stayhealthy.com]) were tested in the study. The two devices have been tested on ambulatory population without disabilities in previous studies and showed good performance in predicting EE [1], [3], [7]-[11]. They also represent typical kinds of AM with different complexity and performance. COSMED K4B2 (COSMED USA, Inc.), a portable gas analyzer and a medical device used for pulmonary gas exchange analysis, was used to measure the volume of oxygen (VO_2) and volume of carbon-dioxide (VCO_2) to estimate energy expenditure in Kcal.

SenseWear RT3

Fig. 1. Activity monitors used in the study.

B. Protocol

The study was approved by the Institutional Review Board at the University of Pittsburgh and the VA Pittsburgh Healthcare System. Subjects were recruited based on the inclusion criteria, that they were between 18 and 60 years of age, manual wheelchair users, have a SCI of T1 or below and are at least six months post-injury. Subjects were asked to obtain a physician release form before participating in the study. The subjects were consented on their arrival. Following which the subjects participated in resting and three activity sessions including wheelchair propulsion, arm-ergometer exercise, and desk work. The activity sessions were counterbalanced and the trials in the activity session were randomized to counter order effects.

Subjects wore SenseWear on the upper right arm, RT3 on the waist and a portable metabolic cart with a face mask while performing the activities. The subjects performed each activity trial for a maximum period of eight minutes, rested for a period of 5 to 10 minutes between each trial and a period of 30 to 40 minutes between the activity sessions. In the propulsion activity the subject's wheelchair was restrained on a stationary dynamometer for two trials. The speed feedback was provided via a monitor in front of the subject. After practicing, the subjects propelled their wheelchair for two trials of 2 miles per hour (2mph Dyno) and 3 miles per hour (3mph Dyno), respectively. In the third trial, the subjects propelled their wheelchair at 3 miles per hour on a flat tiled floor (3mph on tile). The arm-ergometer exercise included three trials of 20 watts resistance at 60 rpm (20W at 60rpm), 40 watts resistance at 60 rpm (40W at 60 rpm) and 40 watts resistance at 90 rpm (40W at 90rpm), respectively. The desk work involved the subjects to use a computer and read a book retrieved from a shelf for four minutes each.

C. Data Collection

The SenseWear, RT3 and portable metabolic cart were synchronized before use. To ensure accuracy of the indirect calorimetry, the system was calibrated for every subject. The data collected from the metabolic cart included EE in kcal/ min, VO_2 and VCO_2 in mL/min/kg for each breath. The data collected from the SenseWear (InnerView Research Software 4.2) included transverse and longitudinal acceleration components sampled at 8Hz, EE in kcal/ min, and heat flux, galvanic skin response and skin temperatures sampled every minute. The data collected from the RT3 included total calories, activity calories, vector magnitude and activity counts in X, Y and Z directions sampled every second.

D. Data Analysis

The energy costs in kcal/min from the SenseWear and the RT3 were compared with those obtained from the metabolic cart after the response stabilized. The collected data from the metabolic cart, SenseWear and RT3 were reduced to a minute data using MATLAB® (Version 7.6.0.324 R2008a, The Mathworks, Inc., USA) data analysis software. The percent difference ($\Delta EE\%$) between the EE measured (EE_{MET}), using the metabolic cart, and the EE estimated (EE_{AM}), by the AM, was obtained by equation (1). Similarly the percent difference in standard deviations ($\Delta EE_{SD}\%$) between the standard deviation of EE measured (EE_{METSD}), using the metabolic cart, and the standard deviation of EE estimated (EE_{AMSD}), by the AM, was obtained by equation (2).

$$\Delta EE\% = (EE_{AM} - EE_{MET})/(EE_{MET}) * 100 \tag{1}$$

$$\Delta EE_{SD}\% = (EE_{AMSD} - EE_{METSD})/(EE_{METSD}) * 100 \tag{2}$$

Statistical analysis was performed using SPSS software (ver. 15.0, SPSS Inc., Chicago, USA). Intraclass correlations (ICCs) were used to assess agreement between the three methods. ICC(3,1) for single measure using two-way mixed model with consistency were performed on the EE estimated by SenseWear and RT3 and EE measured by metabolic cart. An ICC value of ≥ 0.75 is considered good and ≥ 0.9 is deemed excellent [15]. Post statistical analysis, data mining software Weka was used to select attributes from the AM to build EE models for the SenseWear and the RT3 [16].

III. RESULTS

Participants were 6 men with a mean (SD) age of 42.67 (11.15) years, weight of 83.33 (18.98) kg, height of 183.63 (9.29) cm, and body mass index of 24.58 (4.62) kg/m^2. The ethnic origin of five of the participants was Caucasian and one of the participants was African American. The mean

(SD) EE measured using metabolic cart for each activity is shown in Table I.

TABLE I
EE MEASURED USING METABOLIC CART

Activity	Trial	Mean (SD) (kcal/min)
Resting	Resting	1.45 (0.44)
Wheelchair propulsion	2mph on Dynamometer	4.72 (1.69)
	3mph on Dynamometer	6.13 (2.40)
	3mph on Tile surface	3.00 (1.14)
Arm-ergometer exercise	20W at 60 rpm	3.49 (0.53)
	40W at 60 rpm	4.57 (0.46)
	40W at 90 rpm	5.69 (0.66)
Deskwork	Deskwork	1.48 (0.35)

It was found that the SenseWear overestimated EE for resting ($\Delta EE\%$ [$\Delta EE_{SD}\%$]) (+5.78 [-40.66]), wheelchair propulsion (+88.19 [+45.11], +46.20 [-13.36], and +138.21 [+38.84] for the three trials at different intensities, respectively), arm-ergometer exercise (+55.05 [+162.10], +26.92 [+99.95] and +39.17 [+203.23] for the three trials at different intensities, respectively) and deskwork (13.11 [-23.25]). It was also found that the RT3 underestimated EE for resting (-3.06 [-47.85]), wheelchair propulsion (-24.23 [+0.67], -19.42 [+70.17], and -9.98 [+13.60] for the three trials at different intensities, respectively), arm-ergometer exercise (-49.09 [-13.16], -53.69 [+30.55] and -52.08 [+32.92] for the three trials at different intensities, respectively) and deskwork (+0.38 [-17.96]). Figure 1 shows EE over or under estimated by AM.

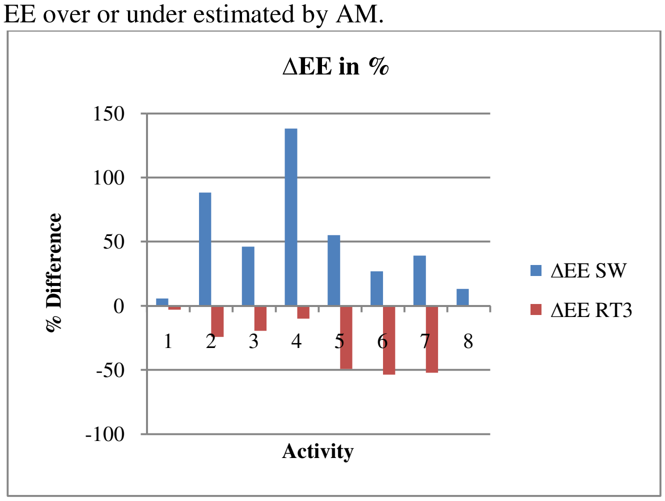

Fig. 2. The column plot of EE over (+ve) or under (-ve) estimated by SenseWear and RT3 compared to EE measured by metabolic cart.

The Intraclass correlation coefficients between EE measured by metabolic cart and EE estimated by SenseWear and RT3 were found to be 0.787 (p<0.0001) and 0.705 (p<0.0001), respectively. Weka was used to find attributes that could be used to model EE equation for SenseWear and RT3. The EE equations found using the Pace Regression classifier with ten fold crossvalidation in Weka for SenseWear and RT3 are indicated in equations (3) and (4) respectively. SenseWear attributes that contributed towards the EE model are average transverese acceleration ($TAVG$), average longitudinal acceleration ($LAVG$), transverse mean absolute deviation ($TMAD$), average galvanic skin resistance ($GSRAVG$), physical activity ($PHYACT$) and EE estimated from SenseWear (EE_{SW}). The physical activity ($PHYACT$) attribute is an output from SenseWear indicating that the subject is performing a physical activity. RT3 attributes that contributed towards the EE model are EE estimated from RT3 (EE_{RT3}), EE from activity (EE_{ACT}), vector magnitude (VM), and acceleration counts in the X, Y, and Z directions ($ACCX, ACCY$ and $ACCZ$). The scatter plots for the EE estimated versus EE measured for SenseWear and RT3 has been shown in figures 3 and 4, respectively. The Intraclass correlation coefficients between the EE measured, by the metabolic cart, and the EE estimated, by the models built for SenseWear and RT3, was found to be 0.944 (p<0.001) and 0.821 (p<0.001), respectively.

$$EE_{MET} = 3.1444 + 0.9597 * TAVG - 3.8 * LAVG + 0.2412 * TMAD + 2.1558 * GSRAVG - 1.1321 * PHYACT + 0.5125 * EE_{SW} \quad (3)$$

$$EE_{MET} = -1.836 + 2.9614 * EE_{RT3} - 2.3773 * EE_{ACT} + 1.6368 * VM - 0.639 * ACCX - 0.9719 * ACCY - 1.434 * ACCZ \quad (4)$$

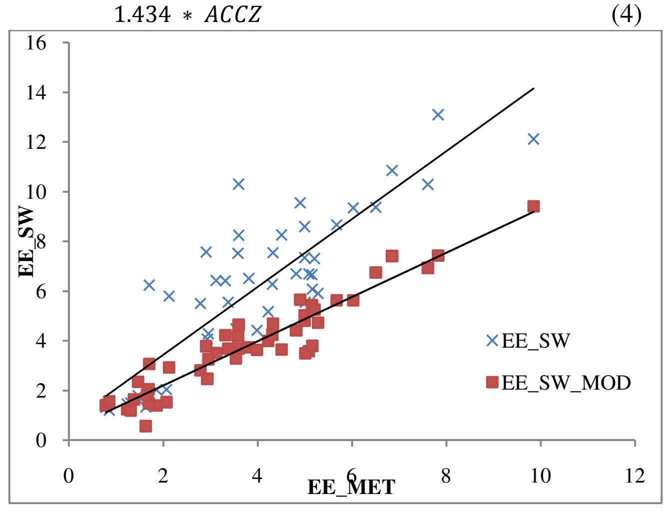

Fig. 3. Scatter plot of EE estimated by SenseWear and EE estimated by the model versus EE measured by metabolic cart.

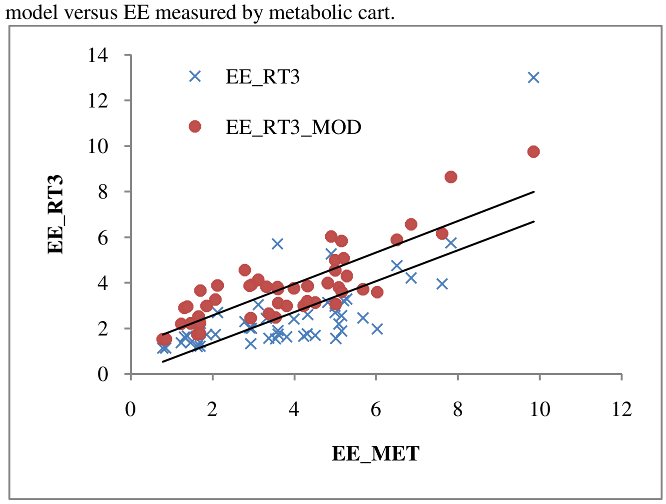

Fig. 4. Scatter plot of EE estimated by RT3 and EE estimated by the model versus EE measured by metabolic cart.

IV. Discussions and Conclusion

This study investigated the use of activity monitors to evaluate energy expenditure in manual wheelchair users with SCI. The information provided by the AM can be used to quantify activities and EE for people with SCI. The EE measured by metabolic cart for the various activities indicated that the wheelchair propulsion at 3mph on dynamometer was the most energy expensive (6.13 kcal/min) activity while resting in their wheelchair was the least energy expensive (1.45 kcal/min). The high SD (1.69, 2.40 and 1.14 kcal/min) during wheelchair propulsion activities may be due to different propulsion patterns used by the subjects [17]. The EE by subjects for the trial at 3mph on the tile surface (3.00 kcal/min) was found to be much less than the EE for the trial at 3mph on the dynamometer (6.13 kcal/min). The reason may be due to lesser resistance offered by the tile surface compared to dynamometer. Good and moderate Intraclass correlations found between the EE estimated, by SenseWear and RT3, and the metabolic cart indicate that these devices could be used to estimate EE in manual wheelchair users with SCI.

AMs utilize acceleration in multiple dimensions and steps to detect from the biomechanical bounce at the waist to classify activities and estimate EE [2]-[3], [9], [18]. The overestimation of EE by SenseWear for most of the activities was probably due to activity misclassification by the SenseWear algorithms [3]. The underestimation of the EE by RT3 may be due to the absence of steps or less vertical movement at the waist against gravity as subjects were seated in their wheelchairs. AM based only on acceleration sensors may fail to detect changes in resistance offered by a particular physical activity like arm-ergometer exercise. Multi-sensor AM like SenseWear, which include galvanic skin response, heat flux and skin temperature, may aid in activity classification requiring physiological monitoring [19].

The equation (3) obtained from Weka clearly indicates that the EE model for SenseWear utilizes acceleration components; EE estimated by SenseWear, which in turn uses multiple sensors, and the average galvanic skin response. However, the EE model obtained for the RT3 utilizes mostly the acceleration components. Excellent and good Intraclass correlation coefficients found between the data obtained using the EE models, for SenseWear and RT3, and the metabolic cart indicate that activity monitors have a great role to play in EE estimation in wheelchair users with SCI. The scatter plots in figures 3 and 4 also indicate that the SenseWear model has a better fit, closer to the unity slope, compared to the RT3 model.

One of the limitations of the current paper is the low number of subjects (n=6) who have participated in the study. The study is ongoing and we plan to recruit more number of subjects for the study. Future work will also evaluate the validity of AMs among wheelchair users with other diagnosis [20].

ACKNOWLEDGMENT

The work is 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 is also supported by PVA 2264-01 and VA Center of Excellence for Wheelchairs and Associated Rehabilitation Engineering B3142C.

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