ORIGINAL ARTICLE

Predicting Energy Expenditure of Manual Wheelchair Users With Spinal Cord Injury Using a Multisensor-Based Activity Monitor

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ABSTRACT. Hiremath SV, Ding D, Farringdon J, Cooper RA. Predicting energy expenditure of manual wheelchair users with spinal cord injury using a multisensor-based activity monitor. Arch Phys Med Rehabil 2012;93:1937-43.

Objective: To develop and evaluate new energy expenditure (EE) prediction models for manual wheelchair users (MWUs) with spinal cord injury (SCI) based on a commercially available multisensor-based activity monitor.

Design: Cross-sectional.

Setting: Laboratory.

Participants: Volunteer sample of MWUs with SCI (N=45).

Intervention: Subjects were asked to perform 4 activities including resting, wheelchair propulsion, arm-ergometer exercise, and deskwork. Criterion EE using a metabolic cart and raw sensor data from a multisensor activity monitor was collected during each of these activities.

Main Outcome Measures: Two new EE prediction models including a general model and an activity-specific model were developed using enhanced all-possible regressions on 36 MWUs and tested on the remaining 9 MWUs.

Results: The activity-specific and general EE prediction models estimated the EE significantly better than the manufacturer's model. The average EE estimation error using the manufacturer's model and the new general and activity-specific models for all activities combined was –55.31% (overestimation), 2.30% (underestimation), and 4.85%, respectively. The average EE estimation error using the manufacturer's model, the new general model, and activity-specific models for various activities varied from –19.10% to −89.85%, –18.13% to 25.13%, and −4.31% to 9.93%, respectively.

Conclusions: The predictors for the new models were based on accelerometer and demographic variables, indicating that movement and subject parameters were necessary in estimating the EE. The results indicate that the multisensor activity monitor with new prediction models can be used to estimate EE in MWUs with SCI during wheelchair-related activities mentioned in this study.

Key Words: Arm ergometry test; Energy expenditure; Physical activity; Rehabilitation; Spinal cord injuries; Wheelchairs.

REGULAR PHYSICAL ACTIVITY (PA) in persons with spinal cord injury (SCI) is associated with positive health benefits, such as increased muscular strength and cardiopulmonary fitness, and decreased deconditioning and pain.[1] However, previous research by Washburn and Hedrick[2] and Fernhall et al[3] showed that only 13% to 16% of persons with SCI reported regular PA. Reduction of PA levels in this population may be due to physiologic changes after SCI, as well as environmental barriers and mobility limitations associated with wheelchair use.[4,5] One of the prerequisites as well as strategies for promoting regular PA is to provide people with an accurate estimate of everyday PA and energy expenditure (EE).[2,3,6] However, persons with SCI, especially those who use manual wheelchairs for mobility, currently do not have an objective means to self-assess their PA participation and free-living EE. Such information can potentially assist manual wheelchair users (MWUs) with SCI to control and regulate their body weight and health.[1,2,7]

With the advancements in miniature sensing technology, there are a number of accelerometry-based activity monitors designed to estimate free-living EE in the ambulatory population.[8,9] St-Onge et al[8] evaluated the validity of a multisensor activity monitor in 45 adults without disabilities under free-living conditions. The mean signed EE estimated daily from the multisensor activity monitor was 117kcal/d (4.7%) lower than the criterion EE measured with doubly labeled water, with an intraclass correlation of .81 ($P<.01$). Berntsen et al[9] evaluated 4 accelerometry-based activity monitors including a multisensor, a single-sensor, and 2 dual-sensor activity monitors against a metabolic cart in 20 adults without disabilities during various activities and found that they underestimated total EE per minute by 9%, 15%, 5%, and 21%, respectively.

To our knowledge, none of the commercially available accelerometry-based activity monitors can accurately estimate EE in MWUs with SCI, as they typically do not consider the types of physical movement MWUs usually perform. Our

List of Abbreviations

EE	energy expenditure
MAE	mean absolute error
MSE	mean signed error
MWU	manual wheelchair user
PA	physical activity
SCI	spinal cord injury

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group has evaluated the performance of a multisensor activity monitor worn on the upper arm and a triaxial accelerometer worn around the waist in 24 MWUs with SCI during resting, wheelchair propulsion, arm-ergometry exercise, and deskwork.[6] Davis et al[10] evaluated the performance of a multisensor activity monitor in 10 MWUs with SCI during wheelchair propulsion on a treadmill at different velocities and gradients.

Despite the fact that current activity monitors cannot accurately estimate EE in MWUs with SCI, researchers have used activity monitors to quantify PA in MWUs with SCI.[11,12] Warms and Belza[11] evaluated the validity of a wrist-worn dual-axial accelerometer to measure community living PA in MWUs with SCI by correlating activity counts from the accelerometer with self-reported activity levels, and the Pearson correlation coefficients varied from .33 to .77. In another study, Washburn and Copay[12] assessed a wrist-worn uniaxial accelerometer in estimating the EE during wheelchair propulsion at 3 different speeds. Significant correlations (r=.52–.66, P<.01) were reported between the activity counts from both wrists and EE over the 3 pushing speeds. Studies by Warms and Belza[11] and Washburn and Copay[12] indicated correlations between activity counts from the activity monitors and PA intensity, but did not provide EE estimation.

The goal of this study was to develop EE prediction models for MWUs with SCI based on a commercially available multisensor activity monitor and evaluate the validity of the new models against criterion EE by a metabolic cart.

METHODS

This study took place at a university-based research facility. The institutional review board at the university approved the study.

Participants

A total of 45 MWUs with SCI volunteered and provided informed consent before their participation in the study. Subjects were included if they were between 18 and 60 years of age, used a manual wheelchair as a primary means of mobility, had an SCI, were at least 6 months postinjury, and were able to use an arm ergometer for exercise. Subjects were excluded if they were unable to tolerate sitting continuously for 4 hours, had active pelvic or thigh wounds, and failed to obtain their primary care physician's consent to participate in the study.

Procedures

The study protocol was described in detail elsewhere.[6] Subjects first completed a basic demographic questionnaire and had their weight,[a] height, and skinfold[b] thickness at 4 body sites (biceps, triceps, subscapular, suprailiac) measured. They were then fitted with a SenseWear[c] on the right upper arm over the triceps, and a K4b2 portable metabolic cart.[d] The activity session started with a resting routine where subjects were instructed to sit still in their wheelchairs. The resting routine was followed by 3 activity routines: wheelchair propulsion, arm-ergometer exercise, and deskwork. The wheelchair propulsion routine included 2 trials of propulsion on a computer-controlled dynamometer with average speeds of .89m/s (2mph) and 1.34m/s (3mph), and 1 trial on a flat tiled surface with an average speed of 1.34m/s (3mph). The arm-ergometer exercise routine consisted of 3 trials at 20W resistance and 60 rotations per minute, 40W and 60 rotations per minute, and 40W and 90 rotations per minute, respectively, on an Angio arm ergometer.[e] During the deskwork routine, subjects performed 2 tasks: reading a book of their choice for 4 minutes and taking a typing test on a computer for 4 minutes. The 3 activity routines were counterbalanced and the trials within each routine were randomized to counter order and carryover effects. Each activity trial lasted for 8 minutes with a resting period of 5 to 10 minutes between each trial and a period of 30 minutes between each activity routine.

Instrumentation and Data Collection

The SenseWear used in this study consisted of a 2-axis accelerometer, a galvanic skin response sensor, a skin temperature sensor, and a near-body temperature sensor. InnerView Research software[c] (version 7.0) was used to retrieve the raw sensor data and estimate EE in kilocalories per minute based on the manufacturer's prediction model. The sensor data included the average, mean absolute deviation, and number of peaks in longitudinal and transverse accelerations at 16Hz; and the average skin temperature, galvanic skin response, and near-body temperature at each minute. The K4b2 was calibrated for each subject as per the manufacturer's instructions. It was synchronized with the SenseWear before use. Cosmed K4b2 software[d] (version 9.0) was used to retrieve the criterion EE data in kilocalories per minute.

Development of EE Prediction Models

Two EE prediction models were developed including a general model (ie, 1 equation for all PA) and an activity-specific model (ie, multiple equations with 1 equation for each type of PA). For both cases, the prediction models were developed based on the data from 80% of the total participants (training group, n=36) and evaluated on the remaining 20% of the total participants (validation group, n=9). A stratified approach based on injury level (paraplegia vs tetraplegia) was performed to select subjects into the training and validation groups. Data preparation involved identifying steady-state conditions for each activity trial based on K4b2.[5,6,13] Steady-state conditions were determined by averaging breath-by-breath EE data over 30-second periods, and EE values having coefficients of variation of less than 10% computed over windows of at least 1 minute were used in the later analysis. To predict the criterion EE, we used 3 types of variables including the sensor data from the SenseWear, demographic data, and customized data derived from the sensor and demographic data. First, the sensor data from the SenseWear provided us with movement and physiologic information of the participant during activities. Second, the demographics data such as sex, age, height, weight, and completeness of injury provided us with wheelchair user–specific characteristics. Third, a number of custom variables including the nonlinear forms of the sensor and demographic data and combinations of the sensor and demographic data were calculated based on the existing literature in the field of PA monitoring and EE estimation in humans. For example, body mass to the power of .75 is a nonlinear variable considered to be a better predictor of EE than the body mass based on Kleiber's law.[14] On similar lines, height divided by mean absolute deviation is a combination variable that normalizes the arm movement by limb length. The custom variables might not have an intuitive definition, but empirically have a better linear relationship than the sensor and demographic data with the criterion EE. The model development process was data driven, which involves selecting the best variables from a pool of sensor, demographic, and custom variables to predict the criterion EE.[15]

A custom "all-possible-regressions" procedure was written in MATLAB software[f] (R2008a) to develop new general and activity-specific EE prediction models. This procedure was exhaustive, but integrated several approaches to avoid overfit-