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ORIGINAL RESEARCH

Estimation of Energy Expenditure for Wheelchair Users Using a Physical Activity Monitoring System

Shivayogi V. Hiremath, PhD,[a,b,c,d] Stephen S. Intille, PhD,[e,f] Annmarie Kelleher, MS,[a,b] Rory A. Cooper, PhD,[a,b,g] Dan Ding, PhD[a,b,g]

From the [a]Department of Veterans Affairs, Human Engineering Research Laboratories, Veterans Affairs Pittsburgh Healthcare System, Pittsburgh, PA; Departments of [b]Rehabilitation Science and Technology, and [c]Physical Medicine and Rehabilitation, University of Pittsburgh, Pittsburgh, PA; [d]Department of Physical Therapy, Temple University, Philadelphia, PA; [e]College of Computer and Information Science, and [f]Department of Health Sciences, Northeastern University, Boston, MA; and [g]Department of Bioengineering, University of Pittsburgh, Pittsburgh, PA.

Abstract

Objective: To develop and evaluate energy expenditure (EE) estimation models for a physical activity monitoring system (PAMS) in manual wheelchair users with spinal cord injury (SCI).

Design: Cross-sectional study.

Setting: University-based laboratory environment, a semistructured environment at the National Veterans Wheelchair Games, and the participants' home environments.

Participants: Volunteer sample of manual wheelchair users with SCI (N=45).

Intervention: Participants were asked to perform 10 physical activities (PAs) of various intensities from a list. The PAMS consists of a gyroscope-based wheel rotation monitor (G-WRM) and an accelerometer device worn on the upper arm or on the wrist. Criterion EE using a portable metabolic cart and raw sensor data from PAMS were collected during each of these activities.

Main Outcome Measures: Estimated EE using custom models for manual wheelchair users based on either the G-WRM and arm accelerometer (PAMS-Arm) or the G-WRM and wrist accelerometer (PAMS-Wrist).

Results: EE estimation performance for the PAMS-Arm (average error ± SD: −9.82%±37.03%) and PAMS-Wrist (−5.65%±32.61%) on the validation dataset indicated that both PAMS-Arm and PAMS-Wrist were able to estimate EE for a range of PAs with <10% error. Moderate to high intraclass correlation coefficients (ICCs) indicated that the EE estimated by PAMS-Arm ($ICC_{3,1}$=.82, P<.05) and PAMS-Wrist ($ICC_{3,1}$=.89, P<.05) are consistent with the criterion EE.

Conclusions: Availability of PA monitors can assist wheelchair users to track PA levels, leading toward a healthier lifestyle. The new models we developed can estimate PA levels in manual wheelchair users with SCI in laboratory and community settings.

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When engaging in regular physical activity (PA), the 3.3 million individuals in the United States who use wheelchairs for mobility face numerous challenges including mobility limitations, changes in physiological conditions, lack of accessible equipment, and environmental barriers.[1-4] These factors affect the PA and sedentary behavior of wheelchair users, leading to higher obesity rates and other secondary conditions.[1,5-7] Research in the general population has shown that behavioral weight loss interventions can produce clinically significant weight loss among obese or overweight adults.[8-12] Many of these interventions rely on self-monitoring of diet, PA, and body weight, and reducing energy intake and increasing energy expenditure (EE).[8-12] In addition, recent research has shown that a combination of behavior and self-monitoring technologies lead to significantly more weight loss than the traditional behavior-based weight loss programs.[13,14] To change the sedentary lifestyle of wheelchair users, we can take an

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approach similar to that for the general population to develop technological interventions that support self-monitoring of PA levels.

Sensor-based PA monitors have been used to track wheelchair movement,[15-19] arm or wrist movements,[20-23] and physiological changes[18,21] for quantifying PAs among persons who use wheelchairs. Garcia-Massó[22] and Nightingale[23] and colleagues indicated that the EE estimated by the activity counts from the GT3X worn on the wrist was highly correlated with criterion EE (housework activities, arm ergometry, and propulsion: $r=.86$[22]; propulsion and deskwork: $r=.93$[23]). Furthermore, Kiuchi et al[20] found that EE estimated by acceleration and angular velocity from an upper arm sensor (left upper arm, $R^2=.75$; right upper arm, $R^2=.87$) was similar to that by a wrist sensor (left wrist, $R^2=.86$; right wrist, $R^2=.68$) during wheelchair propulsion on a treadmill. Hiremath et al[21] used SenseWear, a multisensor-based activity monitor, to develop activity-specific models for 4 PAs, including resting, wheelchair propulsion, arm ergometry, and deskwork, to estimate EE in wheelchair users ($r=.88$). Even though these studies have validated the use of sensor-based activity monitors, none of these devices can concurrently capture both the wheelchair and arm movement, which are essential variables for real-world, day-to-day tracking of PA in wheelchair users.

The primary aim of the study was to develop and validate activity-specific EE estimation models for manual wheelchair users based on a physical activity monitoring system (PAMS). The system consists of a gyroscope-based wheel rotation monitor (G-WRM)[19] for capturing wheelchair movement, and a wearable accelerometer device[24] that tracks upper arm or wrist movements. We evaluated 2 systems based on either the G-WRM and arm accelerometer (PAMS-Arm) or the G-WRM and wrist accelerometer (PAMS-Wrist). The overall EE estimation performance analysis is a 2-step process[21] of sequentially applying the best classification algorithms, which detect the wheelchair-based PAs, and then applying the corresponding activity-specific EE estimation model. Hiremath et al[25] developed classification algorithms such as support vector machines and decision trees that used sensor data from PAMS-Arm and PAMS-Wrist to detect and classify various wheelchair-based PAs in the laboratory, in semi-structured organizational environments, and in unstructured home environments. Hiremath[25] addressed detection of wheelchair-based PAs, whereas this study addresses development and validation of activity-specific EE estimation models for PAMS, making a new and notable contribution in estimating PA levels in wheelchair users. EE is an actionable parameter that individuals may understand and relate to with their meal consumption in kilocalories. PAMS can allow individuals to learn about their PA patterns, which may lead them to performing wheelchair-based PAs that are associated with higher or lower EE values to attain the daily quota of EE toward a healthier lifestyle. The secondary aim of the study was to assess whether the PAMS-Arm will be a better PA level estimator than the PAMS-Wrist.

List of abbreviations:

EE	**energy expenditure**
G-WRM	**gyroscope-based wheel rotation monitor**
ICC	**intraclass correlation coefficient**
MSE	**mean signed error**
PA	**physical activity**
PAMS	**physical activity monitoring system**
SCI	**spinal cord injury**

Methods

The study was approved by institutional review boards of the University of Pittsburgh, US Army Medical Research & Material Command's Human Research Protection Office, and the Veterans Affairs Pittsburgh Healthcare System.

Participants

A total of 45 individuals with spinal cord injury (SCI) took part in the study. Participants were included if they were 18 to 65 years of age, used a manual wheelchair as their primary means of mobility (>80% of their ambulation), and had a diagnosis of SCI. Participants were excluded if they were unable to tolerate sitting for 3 hours, had active pelvic or thigh wounds, had a history of cardiovascular disease, or were pregnant (self-report).

Procedures

The first part of the study was performed in a structured laboratory environment at the Human Engineering Research Laboratories, University of Pittsburgh (n=25) or in the semistructured convention center environment at the National Veterans Wheelchair Games 2012 held in Richmond, VA (n=20). A subsection of the population who took part in the Human Engineering Research Laboratories testing sessions (N=20) participated in the study for a second time in their home environments.

Protocol at Human Engineering Research Laboratories or National Veterans Wheelchair Games

Participants provided informed consent and then answered questions on demographics, wheelchair information, and health and activity history.[25] Body weight was measured using an MX490D wheelchair scale.[a] Body height was either self-reported or measured using a tape.[21,b]

Participants were asked to choose from a list of PAs and perform at least 10 PAs other than resting.[25] Many of the activities were performed at submaximal capacity limiting the order effect on the EE measurement. The type of PAs included propelling their wheelchair at self-selected speeds on various surfaces, or up and down a ramp; being pushed in their wheelchair; playing wheelchair basketball or darts; folding laundry; performing deskwork; using a resistance band; and performing arm ergometry at self-selected speeds and resistances. This list of activities included a range of common everyday activities that involve different parts of the body and varying levels of intensity. Participants were instructed to refrain from eating and exercising at least 2 hours and 12 hours, respectively, before the experiment. The resting trial involved collecting baseline EE for 6 minutes while the participants sat still in their wheelchairs.

During testing, the participants wore a K4b2 portable metabolic cart.[c] Participants also wore a PAMS-Arm and a PAMS-Wrist. All participants performed PAs in their own wheelchairs for a minimum of 6 minutes, with at least a 3-minute break between PAs. Participants rated each activity trial on Borg's Modified Rate of Perceived Exertion Scale (possible scores, 6–20).

Protocol in home environment

The follow-up session involved an activity session of 10 daily activities and a resting trial that the participants were able to perform in their home environments. The participants were provided with an opportunity to perform PAs that they perform on