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Regression Equations for RT3 Activity Monitors to Estimate Energy Expenditure in Manual Wheelchair Users

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Abstract— **Activity monitors (AMs) can assist persons with Spinal Cord Injury (SCI) who use manual wheelchairs to self-assess regular physical activity to move towards healthier lifestyles. In this study we evaluated the validity of an accelerometer-based RT3 AM in predicting energy expenditure (EE) of manual wheelchair users with SCI. Twenty-four subjects performed four types of physical activities including wheelchair propulsion, arm-ergometry exercise, deskwork, and resting in a laboratory setting. Subjects wore two RT3 AMs: an RT3 around the waist (RT3W) per the manufacturer's instruction and an RT3 on the upper arm (RT3A). Criterion EE was collected by a portable metabolic system. The absolute EE estimation error for the RT3W varied from 21.3%-55.2% for different activities. Two EE prediction equations (general and activity-specific) were developed from 19 randomly selected subjects and validated on the remaining 4 subjects for the RT3A, RT3W, and RT3 AMs combined. The results showed that the general and activity-specific regression equations for the RT3A performed better than the RT3W and similar to the RT3 AMs combined. The general EE equation for RT3A consisted of both the demographic variable weight and accelerometer variables showing it is sensitive to subject parameters and upper extremity movement. The activity-specific EE equations for RT3A showed demographic variable weight to be a significant predictor during resting and deskwork and accelerometer variables along with weight to be significant predictors during propulsion and arm-ergometry. The validation results from the activity-specific equations for the RT3A showed that the absolute EE estimation error varied from 12.2%-38.1%. Future work will recruit more subjects and refine the prediction equations for the RT3 AM to quantify physical activity in MWUs with SCI.**

I. INTRODUCTION

Healthy People 2020, a US Department of Health and Human Services planning organization, indicated that individuals with disabilities (54% were non active in 2008) are much less active than individuals without disabilities (32% were non active in 2008) and participate in less regular and vigorous physical activity [1]. Included among people with disabilities are persons with spinal cord injury (SCI) who use manual wheelchairs and have adopted a sedentary lifestyle due to physiological changes, lack of accessible environments like gymnasiums and the limited scope of recreation therapy in rehabilitation centers. Studies by Washburn et al. and Fernhall et al., have reported that only 13-16% of persons with SCI reported regular physical activity [2], and the majority of people with SCI reported virtually no regular physical activity [3].

One of the ways to promote regular physical activity in manual wheelchair users (MWUs) with SCI is to empower them with tools to self-assess regular physical activity levels [3]. Although self-reporting tools are inexpensive and widely used, they are subject to recall bias and social desirability bias, and unable to quantify physical activities [4]. More recently, sensor-based activity monitors (AMs) have demonstrated the ability to accurately assess physical activity in free-living environments [5, 6] .

Our previous research evaluated the performance of two specific sensor-based AMs, SenseWear (SW) and RT3 in estimating energy expenditure (EE) in 24 MWUs with SCI during various activities such as resting, wheelchair propulsion, arm-ergometry and deskwork. The SW and RT3 AMs had EE estimation errors ranging from 20.1% to 130.0% and 17.0% to 46.9%, respectively, compared to indirect calorimetry [7]. These results indicated that neither of the AMs can be directly used as an appropriate tool for measuring physical activity in MWUs with SCI. In another study of 10 MWUs with SCI Davis et al. also showed that SW AM overestimated EE (14.3±6.0 kJ/min) compared to indirect calorimetry (11.4±4.0 kJ/min) during various wheelchair propulsion trials on a treadmill with different velocity and gradient combinations [8]. To see if we could provide more accurate EE estimation for MWUs with SCI, we developed activity-specific regression equations for the SW AM, which significantly reduced EE estimation errors for resting (22.6%), wheelchair propulsion (16.6-20.6%), arm-ergometry (6.8-32.9%) and deskwork (20.8%) activities [9].

The objective of this study was to develop and evaluate new EE prediction equations for the off-the-shelf RT3 AMs in MWUs with SCI. Two EE prediction equations (general and activity-specific) were developed for the RT3 on the arm, RT3 on the waist, and the two RT3 AMs combined. We hypothesized that the prediction equations for the RT3 on the arm will predict EE better than the RT3 on the waist in this population, and the prediction equations based on the two RT3 AMs combined will predict EE better than the RT3 on the arm alone.

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II. METHODOLOGY

A. Protocol

The study was approved by the Institutional Review Boards at the University of Pittsburgh and the VA Pittsburgh Healthcare System. Subjects were included in the study if they were between 18 and 60 years, used a manual wheelchair as a primary means of mobility, had an SCI of T1 or below, were at least six months post-injury, and were able to use an arm-ergometer for exercise. Subjects were excluded from the study if they were unable to tolerate sitting for 4 hours, had active pelvic or thigh wounds, or failed to obtain their primary care physician's consent to participate in the study. All subjects provided a written informed consent prior to their participation in the study.

The protocol started with a pre-activity session during which subjects completed a questionnaire collecting information including demographic variables such as age, level and completeness of SCI, and current health and physical activity status. In addition, the investigators measured weight, height and skinfolds at biceps, triceps, subscapular and suprailiac. During the activity session, subjects wore a portable metabolic cart K4b2 connected to a face mask, a Polar heart rate monitor on their chest, an RT3 on the upper left arm (RT3A) on triceps muscles, and an RT3 on the waist (RT3W) near the anterior superior iliac spine. The activity session consisted of resting and three activity routines including wheelchair propulsion, arm-ergometer exercise, and deskwork. During the resting session, subjects were required to be seated still in their wheelchairs for a period of eight minutes while the K4b2 and the RT3 AMs collected data. The propulsion routine included three trials of wheelchair propulsion, i.e., 0.89m/s (2mph) and 1.34m/s (3mph) on a computer controlled dynamometer and 1.34m/s (3mph) on a tiled surface. The resistance offered by the dynamometer simulated propelling on a slope of +2°. The arm-ergometer exercise included three trials at different intensities, i.e., 20 watts (W) resistance at 60 rotations per minute (rpm), 40W at 60rpm, and 40W at 90rpm. During the deskwork routine, subjects typed on a computer using typing software and read a book of their choice. Overall, subjects were asked to perform each activity trial for up to 8 minutes with a resting period of 5 to 10 minutes between each trial and a period of 30 to 40 minutes between each activity routine. The activity routines, except for resting, were counterbalanced, and the trials within each activity routine were randomized in an effort to reduce order effects. All subjects completed the eight activity trials.

B. Instrumentation and Data Collection

The criterion EE was measured by a COSMED K4b2 (COSMED srl, Rome, Italy). This device consists of a gas analyzer that measures the volume of oxygen (VO_2) and volume of carbon-dioxide (VCO_2) to estimate EE in Kcal/min. The data collected from the K4b2 was EE in kcal/min. Data from the K4b2 for two trials, including one 3mph propulsion trial on the tiled surface and one resting trial, were discarded due to device malfunction. The RT3 (Stayhealthy Inc., Monrovia, CA) uses sensor data in addition to height, weight, age, and gender of the subjects to estimate the EE. To ensure accuracy of the data collection, the K4b2 was calibrated for every subject and time-synchronized with the RT3 AMs. The data collected from the RT3 included total calories in kcal/min, activity counts in X, Y and Z directions, and resultant activity counts sampled every second. Previous studies have tested the RT3 AM on ambulatory populations without disabilities and have shown that RT3 AMs have good performance in predicting EE [5]. Data from the RT3 on the waist for the eighth participant was lost due to a device malfunction.

C. Data Analysis

The data analysis software was written in MATLAB® (ver. 7.10, The Mathworks Inc. MA, USA) to process and analyze data from the K4b2 and the RT3 AMs. Steady-state conditions during the activity trials were determined by averaging breath-by-breath EE data over 30 second periods, and identifying EE values having coefficients of variation less than 10% computed over windows of at least 1 minute. The EE values that had less than 10% variation over a minute window were averaged and used for the analysis [10]. Three trials, including a resting trial, a 2mph propulsion trial on dyno, and a deskwork trial that did not yield steady-state conditions were discarded. All statistical analysis was performed using SPSS software (ver. 15.0, SPSS Inc. Il., USA), with the statistical significance set at an alpha level of 0.05. We evaluated the performance of the RT3 worn on the waist as prescribed by the manufacturer in predicting EE when compared to the K4b2 [7].

We developed EE prediction equations for the RT3A, RT3W and RT3 AMs combined through forward stepwise multiple regression analysis. Steady state data from 19 randomly chosen subjects from the 23 subjects (excluding the eighth subject whose RT3W data was discarded) were used to develop the regression equations. The steady state data for the remaining 4 subjects was used as a validation group. Two types of regression equations were developed, including a general equation for all the activities combined and activity-specific equations for resting, propulsion, arm-ergometry exercise and deskwork activities. The dependent variable was the criterion EE measured using the K4b2. The independent variables included the acceleration variables, i.e. activity counts in X, Y, Z and resultant directions, and demographic variables including age and weight. Data from the activity trials for all subjects within each activity routine were treated as independent observations. The prediction equations were cross-validated with the data from the validation group by computing the absolute differences and absolute percentage errors between the predicted and the criterion EE.

III. RESULTS

Participants (n=24) were 19 men and 5 women with a mean ± SD 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% ± 7.3%. The SCI level varied from T3 to L4, with 11 of the 24 subjects having a complete injury and the remaining 13 subjects having an incomplete injury. Self-reported PA information indicated that 10 subjects performed regular PA; 8 performed occasional PA; and 6 performed no regular PA. Table I shows the criterion EEs by the K4b2, the estimated EEs by RT3W, and absolute differences and percentage errors between them for each activity trial.

TABLE I
RT3W ESTIMATION ERRORS USING MANUFACTURER'S EQUATIONS

	K4b2	RT3W	RT3W Prediction Error	
Trial	Mean (SD) (kcal/min)	Mean (SD) (kcal/min)	kcal/min	Percentage (%)
Resting	1.08 (0.25)	1.33 (0.27)	0.28 (0.21)	27.91 (17.88)
2mph on Dyno	3.85 (1.62)	4.23 (2.32)	1.69 (2.18)	45.37 (41.72)
3mph on Dyno	4.77 (2.18)	6.03 (3.99)	2.46 (3.30)	52.68 (63.42)
3mph on Tile	2.77 (1.09)	3.72 (1.87)	1.24 (1.67)	51.36 (64.53)
20W at 60 rpm	3.07 (0.51)	2.94 (1.94)	1.52 (1.93)	50.38 (43.78)
40W at 60 rpm	4.42 (0.60)	3.34 (2.08)	1.97 (1.93)	45.22 (21.10)
40W at 90 rpm	5.40 (0.99)	5.47 (3.67)	2.92 (3.55)	55.24 (40.01)
Deskwork	1.29 (0.29)	1.42 (0.39)	0.27 (0.30)	21.31 (10.77)

Table II shows the adjusted R-square and the standard error of estimate (SEE) from the regression analysis. For both the general equation and activity specific equations, the RT3A performed better than the RT3W and similar to the RT3A and RT3W combined. The general and activity-specific equations for RT3A are shown in equations 1-5. Table III shows the predictors of the regression equations for the RT3A. Tables IV and V show the validation results for the general and activity-specific equations.

TABLE II
STATISITCS FOR GENERAL AND ACTIVITY-SPECIFIC EE EQUATIONS FOR RT3A, RT3W, AND RT3A AND RT3W COMBINED

General equations	
RT3A	Adj. $R^2 = 0.697$, SEE =1.02, F(1,143) = 12.738, p< 0.001
RT3W	Adj. $R^2 = 0.440$, SEE = 1.38, F(1,142)= 4.961, p=0.027
RT3A and RT3W	Adj. $R^2 = 0.707$, SEE = 1.00, F(1,142)= 5.704, p=0.018
Activity-specific equations	
Resting trial	
RT3A, RT3W, RT3A & RT3W	Adj. $R^2 = 0.477$, SEE =0.18, F(1,14) = 15.603, p =0.001
Propulsion trial	
RT3A	Adj. $R^2 = 0.830$, SEE =0.77, F(1, 51) = 46.780, p<0.001
RT3W	Adj. $R^2 = 0.687$, SEE = 1.04, F(1,51)= 4.546, p=0.038
RT3A and RT3W	Adj. $R^2 = 0.864$, SEE = 0.69, F(1,50)= 13.578, p=0.001
Arm-ergometry trial	
RT3A	Adj. $R^2 = 0.474$, SEE =0.87, F(1, 54) = 9.890, p=0.003
RT3W	Adj. $R^2 = 0.247$, SEE =1.04, F(1, 54) = 7.870, p=0.007
RT3A and RT3W	Adj. $R^2 = 0.474$, SEE =0.87, F(1, 54) = 9.890, p=0.003
Deskwork trial	
RT3A, RT3W, RT3A and RT3W	Adj. $R^2 = 0.405$, SEE =0.22, F(1, 16) = 12.569, p=0.003

General equation for RT3A

$$EE_{General} = -0.092 + 0.091 * ACCXarm + 0.021 * weight + 0.029 * ACCYarm \quad (1)$$

Activity-specific equations for RT3A

$$EE_{Resting} = 0.456 + 0.008 * weight \quad (2)$$

$$EE_{Propulsion} = -2.199 + 0.076 * ACCYarm + 0.040 * weight + 0.031 * ACCXYZarm \quad (3)$$

$$EE_{Arm-ergometry} = 1.626 + 0.075 * ACCXarm + 0.017 * weight \quad (4)$$

$$EE_{Deskwork} = 0.645 + 0.008 * weight \quad (5)$$

TABLE III
PREDICTORS FOR GENERAL AND ACTIVITY-SPECIFIC EE EQUAIONS FOR RT3A AM

General equation for RT3A	
RT3A	Predictors: ACCXarm(β=0.60, p<0.001), weight (β=0.26,p<0.001), ACCYarm (β=0.23,p<0.001)
Activity-specific equations for RT3A	
Resting	Predictors: weight (β=0.71,p=0.001)
Propulsion	Predictors: ACCYarm (β=0.58,p<0.001), weight (β=0.47,p<0.001), ACCXYZarm (β=0.40,p<0.001)
Arm-ergometry	Predictors: ACCXarm (β=0.58, p<0.001), weight (β=0.31, p=0.003)
Deskwork	Predictors: weight (β=0.66, p=0.003)

TABLE IV
EE ESTIMATION ERRORS USING GENERAL EQUATIONS

	RT3A	RT3W	RT3A and RT3W
Trial	Percentage (%)	Percentage (%)	Percentage (%)
Resting	113.68 (76.11)	183.38 (71.08)	116.87 (76.29)
2mph on Dyno	37.43 (15.69)	12.89 (12.49)	33.45 (14.43)
3mph on Dyno	32.76 (19.11)	12.94 (12.43)	28.69 (17.28)
3mph on Tile	45.74 (10.90)	24.99 (24.05)	41.85 (10.33)
20W at 60 rpm	28.20 (28.72)	28.60 (18.76)	25.94 (29.29)
40W at 60 rpm	22.27 (9.67)	35.77 (10.63)	23.43 (9.76)
40W at 90 rpm	14.12 (18.88)	36.96 (12.17)	14.14 (19.19)
Deskwork	51.69 (77.36)	124.31 (105.75)	55.92 (80.96)

TABLE V
EE ESTIMATION ERRORS USING ACTIVITY-SPECIFIC EQUATIONS

	RT3A	RT3W	RT3A and RT3W
Trial	Percentage (%)	Percentage (%)	Percentage (%)
Resting	18.62 (21.71)	18.62 (21.71)	18.62 (21.71)
2mph on Dyno	26.55 (30.39)	25.53 (27.90)	26.99 (28.24)
3mph on Dyno	26.46 (15.52)	27.51 (20.00)	23.96 (16.81)
3mph on Tile	37.09 (31.56)	35.52 (39.64)	31.11 (38.05)
20W at 60 rpm	38.14 (26.87)	41.57 (28.98)	38.14 (26.87)
40W at 60 rpm	16.07 (10.94)	16.12 (16.40)	16.07 (10.94)
40W at 90 rpm	12.15 (15.93)	22.91 (4.78)	12.15 (15.93)
Deskwork	23.21 (28.77)	23.21 (28.77)	23.21 (28.77)

IV. DISCUSSIONS AND CONCLUSION

Regular physical activity in MWUs with SCI is positively associated with health benefits such as reduced risk of cardiovascular diseases and other chronic conditions, and improved psychological well-being [3]. Activity Monitors can help quantify and provide accurate estimates of physical activity in terms of EE, thereby helping promote healthier lifestyles for MWUs with SCI. In this study we have evaluated the performance of general and activity-specific prediction equations to estimate EE for RT3 AMs worn on the arm and waist.

The results (Table I) showed that the default EE outputs from the RT3W were not accurate when compared with the criterion EE with the absolute EE estimation errors varying from 21.3% to 55.2%. The errors were much higher than those for the ambulatory population (<2%) [5]. Though the new activity-specific prediction models improved the EE estimation accuracy, the absolute errors still range from 12.2% to 38.1% (Table V). From Table II, it seemed that the RT3 worn on the upper arm yielded a better regression model than the one worn on the waist. However, the validation results from Table V showed that the location of wearing the RT3 did not make much difference. Moreover, combining the data collected from two RT3 AMs did not yield more accurate estimation.

When looking into the predictors of the activity-specific regression equations for the RT3A (Table III), we note that the body weight was a significant predictor during resting and deskwork, while accelerometer variables such as activity counts in X, Y, and resultant directions along with the body weight predicted EE during propulsion and arm-ergometry. Consideration of accelerometer variables during wheelchair propulsion and arm-ergometry allows these EE equations to be sensitive to upper extremity movements during these activities.

One of our previous studies developed new EE prediction equations for a SenseWear (SW) Armband (BodyMedia Inc., Pittsburgh, USA) for MWUs with SCI [9]. When comparing the validation results between the RT3A and the SW in the previous study, the activity-specific equations for the RT3A had more accurate EE estimation only for the resting (18.6% vs. 22.6%) and arm-ergometry trial at 40W at 60rpm (16.1% vs. 18.9%). For the rest of the activity trials, the SW AM outperformed the RT3A. Better overall performance of the SW AM may be due to the high sampling rate of 16Hz in the SW AM, access to raw acceleration in m/s^2, and using acceleration features such as the mean and the mean absolute deviation as EE predictors. For the RT3, the sampling rate was only 1Hz and we were unable to retrieve raw acceleration data, as the manufacturer only provides activity count data that is processed using proprietary algorithms.

There are several limitations of this study including limited number of physical activities, small sample size (n=24), and testing the AMs only in MWUs with SCI. The study is ongoing and we hope to recruit more subjects. The study was limited to persons with SCI in an effort to reduce the effect of different disabilities towards the development of equations. In this study we limited the analysis to linear EE regression equations because wearable devices such as RT3 have limited computational power. Future work will involve extracting features of activity counts, using nonlinear variables and rigorous cross-validations to develop equations for RT3 AMs. Furthermore, we will aim to develop equations for AMs among wheelchair users with other disabilities.

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REFERENCES

[1] U.S. Department of Health and Human Services, (Jan 10, 2011). "Healthy People 2020.", Washington, DC. U.S. Department of Health and Human Services. Available: http://www.healthypeople.gov/2020/topicsobjectives2020/overview.aspx?topicid=9.

[2] R. Washburn, B. N. Hedrick. "Descriptive epidemiology of physical activity in university graduates with locomotor disabilities", *International Journal of Rehabilitation Research*, vol. 20(3), pp. 275-287, 1997.

[3] B. Fernhall, K. Heffernan, S. Y. Jae, B. Hedrick. "Health implications of physical activity in individuals with spinal cord injury: a literature review", *Journal of Health and Human Services Administration*, vol. 30(4), pp. 468-502, 2008.

[4] C. Warms. "Physical activity measurement in persons with chronic and disabling conditions", *Family Community Health*, vol. 29(S1), pp. 78S-88S, 2006.

[5] M. P. Rothney, E. V. Schaefer, M. M. Neumann, L. Choi, K. Y. Chen. "Validity of physical activity intensity predictions by ActiGraph, Actical, and RT3 accelerometers", *Obesity*, vol. 16(8), pp. 1946-1952, 2008.

[6] M. St-Onge, D. Mignault, D. Allison, R. Rabasa-Lhoret. "Evaluation of a portable device to measure daily energy expenditure in free-living adults", *American Journal of Clinical Nutrition*, vol. 85(3), pp. 742-749, 2007.

[7] S. V. Hiremath, D. Ding. "Evaluation of activity monitors in manual wheelchair users with paraplegia", *Journal of Spinal Cord Medicine*, vol. 34(1), pp. 110-117, 2011.

[8] G. M. Davis, R. A. Tanhoffer, l. I. P. Tanhoffer, K. R. Pithon, E. H. Estigoni, J. Raymond. "Energy Expenditures during Wheelchair Propulsion Derived from a Body-worn Sensor versus Indirect Calorimetry", *Medicine and Science in Sports and Exercise*, vol. 42(5), pp. 335, 2010.

[9] S. V. Hiremath, D. Ding. "Predicting Energy Expenditure of Manual Wheelchair Users using a Wearable Device", *In: Proceedings of RESNA 2011 Annual Conference, Toronto, Canada*. 2011.

[10] R. D. Starling. "Use of Doubly Labeled Water and Indirect Calorimetry to Assess Physical Activity," in *Physical Activity Assessments for Health-Related Research*, 1st ed., G. J. Welk, Ed. Human Kinetics: Champaign, IL. 2002, 197-209.