Department of Veterans Affairs

JRRD Volume 42, Number 5, Pages 617–624
September/October 2005
Journal of Rehabilitation Research & Development

Heart rate as a predictor of energy expenditure in people with spinal cord injury

Amy M. Hayes, PT, MS;[1] Jonathan N. Myers, PhD;[2–3*] Monica Ho;[1] Matthew Y. Lee, MS;[1] Inder Perkash, MD;[1,3] B. Jenny Kiratli, PhD[1]

[1]Spinal Cord Injury Center, Department of Veterans Affairs Palo Alto Health Care System (VAPAHCS), Palo Alto, CA; [2]Cardiology Division, VAPAHCS, Palo Alto, CA; [3]Stanford University, Palo Alto, CA

Abstract—This study evaluated the accuracy of heart rate calibrated from a maximum exercise test for predicting energy expenditure during five activities of daily living (ADL) in participants with spinal cord injury (SCI). Thirteen individuals with SCI underwent maximum exercise testing, followed by portable heart rate and metabolic testing during five ADL. A regression equation was developed from heart rate and oxygen uptake responses during the maximum exercise test for each subject. Based on this individualized equation, heart rate measured during the ADL was used to estimate energy expenditure for each participant. Predicted energy expenditure from heart rate was compared with that measured by indirect calorimetry with the use of oxygen uptake. Heart rate derived from the individualized regression equations explained 55% of the variance in measured energy expenditure, compared with only 8.3% from heart rate alone. However, calibrated heart rate consistently overestimated the actual kilocalories used; on average, the estimated energy expenditure was roughly 25% higher than that measured by oxygen uptake. Heart rate can be used as a gross estimate of energy expenditure during higher-intensity ADL in people with SCI when individual calibration of heart rate from maximum exercise testing is used.

Key words: activities of daily living, cardiovascular disease, energy expenditure, exercise testing, heart rate, oxygen uptake, predicted energy expenditure, spinal cord injury.

INTRODUCTION

Obesity and physical inactivity are among the key modifiable risk factors for cardiovascular disease (CVD) and are the focus of several healthcare initiatives aimed at reducing the prevalence of this condition [1–3]. Guidelines on specific energy expenditure from the American Heart Association, the American College of Sports Medicine, and the Centers for Disease Control and Prevention recommend people expend at least 150 to 200 kcal through moderate-intensity physical activity on most, and preferably all, days of the week to decrease CVD risk [2,4]. People with spinal cord injury (SCI) are reported to have greater CVD risk, including a higher prevalence of obesity and abnormal blood lipid levels (specifically abnormal high density lipoprotein [HDL] and an increased ratio of total cholesterol to HDL) [5], in addition to decreased muscle mass and decreased physical

---

Abbreviations: ADL = activities of daily living, CVD = cardiovascular disease, HDL = high density lipoprotein, RER = respiratory exchange ratio, SCI = spinal cord injury, $\dot{V}CO_2$ = carbon dioxide production, $\dot{V}O_2$ = oxygen uptake.

This material was based on work supported by the Department of Veterans Affairs, Rehabilitation Research and Development Service (B2549R), with partial financial support from the Paralyzed Veterans Association Bay Area and Western Chapter as part of the sponsored Summer Scholar Program.

*Address all correspondence to Jonathan N. Myers, PhD; VAPAHCS, Cardiology Division (111C), 3801 Miranda Avenue, Palo Alto, CA 94304; 650-493-5000, ext. 64661; fax: 650-852-3473. Email: Drj993@aol.com

DOI: 10.1682/JRRD.2004.12.0150

function. Typical physical exertion through daily activities in those with SCI has been reported inadequate for maintaining cardiovascular fitness [6]. While resources are available for healthcare providers to help nondisabled individuals meet these recommendations, such as physical activity compendiums, multivariate equations, activity monitors, or heart rate as an estimate of energy expenditure, research in this area is lacking for individuals with SCI. Work has begun on development and validation of an SCI-specific compendium of physical activities derived from directly measured oxygen uptake ($\dot{V}O_2$), but it remains to be completed and implemented [7].

The models that exist for energy expenditure estimation in the ambulatory population, current compendium standards, activity questionnaires, predictive equations, and heart rate methods tend to overestimate energy expenditure from physical activity in people with SCI [8–9]. Estimation of energy expenditure in those with SCI is further complicated by the need to account for lesion level and completeness of the injury [9], which affect the amount of active muscle mass. These factors, along with the degree of autonomic dysfunction, make the estimation of energy expenditure by heart rate alone or by predictive equations developed for nondisabled individuals problematic [8]. Although doubly labeled water and direct calorimetry techniques have provided valid estimations of energy expenditure in people with SCI [8–9], they are expensive and only feasible in research settings.

This pilot study evaluated the accuracy of heart rate for predicting measured energy expenditure during five activities of daily living (ADL) in participants with SCI.

METHODS

Subjects

Thirteen subjects with SCI participated in the study (twelve males and one female). Subject characteristics are presented in **Table 1**. Three participants were tetraplegic and ten were paraplegic. The mean (± standard deviation) age was 50.0 ± 12.9 years (range 30–72 yr). All subjects had traumatic SCI of at least 1-year duration and were functionally nonambulatory (i.e., no capacity to ambulate or a limited capacity to ambulate for weight-bearing or exercising only). Subjects were excluded from participation if they had comorbid neurological conditions, other serious medical conditions, or were currently taking beta-blockers. All participants were tested with their own manual wheelchairs. Written informed consent was obtained with a protocol approved by the Stanford University Institutional Review Board.

Exercise Testing

All subjects completed maximum exercise tests using a manually incremented arm ergometry protocol. Testing was

Table 1.
Subject characteristics and results from maximum exercise test. Pearson's correlation coefficient (*r*) between peak heart rate (HR) and oxygen uptake ($\dot{V}O_2$).

Subject	Age	Lesion Level	ASIA Class	Gender	Peak HR	Peak $\dot{V}O_2$	*r*
1	50	C5	C	M	100	14.58	0.75
2	60	C6	C	M	96	13.20	0.97
3	45	C7	B	M	126	15.20	0.95
4	35	T3	A	M	159	19.70	0.63
5	59	T4	A	M	124	10.66	0.89
6	64	T4	A	M	144	11.30	0.96
7	35	T4	B	M	172	22.49	0.83
8	58	T5	A	M	168	17.11	0.78
9	42	T6	A	M	216	27.17	0.90
10	38	T5	B	M	116	12.92	0.97
11	30	T5	A	M	178	15.03	0.80
12	53	T12	D	M	118	19.66	0.96
13	72	L5–S1	C	F	141	13.67	0.89

ASIA Class = American Spinal Cord Injury Association—classifications A to D (impairment scale), C = cervical, F = female, L = lumbar, M = male, S = sacral, T = thoracic; lesion levels are vertebrae numbers.

performed in the upright seated position with a Monarch (Varberg, Sweden) arm ergometer mounted to an adjustable table. Subjects were requested to maintain the arm crank cadence at 60 rpm throughout the test. Changes in resistance of the arm ergometer were individualized (ranging from 1 to 10 W/min) such that the test duration ranged from 8 to 12 minutes. Standard 12-lead electrocardiograph and $\dot{V}O_2$ data were obtained throughout the exercise test and recovery period. To exclude artifacts, we rechecked heart rates after each test using calipers. Blood pressure was measured while the subject was in the sitting position before the test and immediately afterwards and was monitored for a minimum of 8 minutes while the subject was in recovery. Exercise was continued until volitional fatigue occurred, the subject was no longer able to maintain 60 rpm at a given workload, or both. The Borg 6-20 scale of perceived exertion was used to quantify subjective effort at 1-minute intervals [10].

$\dot{V}O_2$ and other cardiopulmonary exercise responses (including minute ventilation, tidal volume, respiratory rate, and carbon dioxide production [$\dot{V}CO_2$]) were obtained with the COSMED K4b^2 system (Rome, Italy). Tidal volume, minute ventilation, respiratory rate, fraction of inspired oxygen, and fractions of expired oxygen and CO_2 were measured, and $\dot{V}O_2$, $\dot{V}CO_2$, and respiratory exchange ratio (RER) were calculated. Energy expenditure was derived from measured $\dot{V}O_2$ and expressed as kilocalories/minute.

Activities of Daily Living Measurement Procedures

All subjects completed a series of five ADL. Each of the activities was standardized with a script that the subjects read. Subjects were instructed to perform at their usual paces. A rest period of at least 3 minutes preceded each test, and each ADL was performed for approximately 5 minutes. The activities were chosen to incorporate common household tasks, as well as to vary the energy cost. The tasks included (1) performing desk work, (2) loading and unloading a dishwasher, (3) transferring to and from a wheelchair to a bed, (4) wheeling at a self-selected pace over tile, and (5) performing laundry tasks (placing towels into a washing machine, transferring towels from the washing machine to a dryer, unloading the dryer, and folding the towels). The level of perceived exertion (Borg 6-20 scale) was determined at the beginning and end of each ADL.

Portable Oxygen Uptake and Heart Rate Testing

The COSMED K4b^2 portable gas exchange system was used to collect $\dot{V}O_2$ data during the ADL, and calculations for the cardiopulmonary exercise data were performed as just described. Subjects were fitted with appropriately sized face masks and asked to breath through their mouths throughout testing. Breath-by-breath metabolic data were acquired for pulmonary gas exchange parameters, including $\dot{V}O_2$, $\dot{V}CO_2$, tidal volume, ventilation, respiratory frequency, and RER. Energy expenditure was derived from the metabolic data and expressed in kilocalories [11]. For the energy expenditure measurements and comparison with heart rate, metabolic data were expressed in rolling 30-second averages sampled every 10 seconds. A wireless, double-electrode Polar® (Kempele, Finland) monitor was used to measure heart rate.

Several groups have recently performed validation studies on the portable COSMED system [11–14]. These studies have included comparisons of cardiopulmonary responses obtained from the portable COSMED system with both stand-alone metabolic systems and mass spectrometers. Maiolo et al., for example, reported differences in $\dot{V}O_2$ measurements between COSMED and mass spectrometer recordings that ranged from 1 to 5 percent at different exercise intensities [13].

Data Analysis

The relationship between heart rate and energy expenditure was assessed in two ways. First, linear regression was used to assess the association between heart rate alone and directly measured energy expenditure during the ADL. This was followed by estimation of energy expenditure from the individualized relationship between heart rate and $\dot{V}O_2$ for each subject with heart rate data from their maximum exercise test (termed "calibrated" energy expenditure). We calculated calibrated energy expenditure by taking the average heart rate every 30 seconds during exercise testing and regressing it on the average measured energy expenditure values for the corresponding time. We then used these linear regression equations to convert 30-second heart rate measurements during the ADL into predicted energy expenditure values. Average measured (from the metabolic system) and predicted (from calibrated heart rate) energy expenditure/minute was calculated during rest and each ADL and also for the entire measurement period. We used the last minute of each rest period between activities to calculate the resting data. Pearson correlation coefficients were calculated for determining the associations between predicted and measured energy expenditure for each activity and the total measurement period. Heart rate without individual calibration was also compared with the measured energy expenditure.

We used multiple regression to determine whether perceived exertion, along with heart rate, added significantly to the explanation of variance in energy expenditure. Differences between predicted and measured energy expenditure were determined by paired *t*-tests for each activity and the total measurement period. We also explored whether prediction of energy expenditure differed by group (tetraplegic vs paraplegic) with unpaired *t*-tests.

RESULTS

Heart rate alone was significantly, but weakly, correlated with energy expenditure during the ADL overall; only 8.3 percent of the variance in energy expenditure was explained by heart rate ($p < 0.001$). None of the ADLs were strongly correlated with heart rate alone. Conversely, predicted energy expenditure (from heart rate calibrated with the individualized exercise tests and measured energy expenditure) for all ADL together was highly correlated ($r = 0.74$, $p < 0.001$) and explained 55 percent of the variance in energy expenditure. In addition, modest-to-high-correlation coefficients were observed for all ADL measured (**Table 2**). The variance in energy expenditure explained by calibrated heart rate for each of the activities ranged from 28 to 88 percent. The **Figure** illustrates the relationship between measured energy expenditure and that estimated by heart rate calibrated from the exercise tests for the strongest (wheeling, $r = 0.94$) and the weakest (desk work, $r = 0.53$) associations. Significant differences were observed between predicted and measured values for desk work, wheeling on tile, laundry, and rest. Energy expenditure estimated from calibrated heart rate was greater by 5 to 48 percent than measured energy expenditure, with the larger differences observed for the most sedentary activities (rest and desk work) (**Table 2**). Perceived exertion did not add significantly to the estimation of energy expenditure.

The correlation coefficients between measured and estimated energy expenditure and corresponding *p*-values for the different impairment levels are listed in **Table 3**. For the total period of activity, the relationship between measured and estimated energy expenditure was similar for subjects with tetraplegia and paraplegia ($r = 0.84$ and 0.78, respectively). Comparisons of percentage of peak heart rate reached between those with paraplegia and tetraplegia are shown in **Table 4**. The percentage of peak heart rate reached during all the different activities was significantly higher for those with tetraplegia compared with those with paraplegia, with a range of 12 to 24 percent higher.

DISCUSSION

In this preliminary study, we examined the accuracy of heart rate for estimating energy expenditure in a SCI population. Our major findings included (1) heart rate, when derived from an individualized regression equation based on an exercise test, can grossly estimate energy expenditure during ADL in persons with SCI; (2) this estimation is more accurate for higher intensity activities; (3) heart rate alone, without individual calibration from an exercise test, poorly estimates energy expenditure; and

Table 2.
Mean ± standard deviation, Pearson's correlation coefficient (*r*), percent difference, and paired *t*-test for measured vs estimated energy expenditure for ADL and rest.

Activity	Measured (kcal/min)	Estimated (kcal/min)	*r*	*p*-Value (*r*)	Difference (%)	*p*-Value (Paired *t*-Test)
Desk Work	1.68 ± 0.31	2.46 ± 0.65	0.53	0.063	47.7	0.0002
Dishes	2.37 ± 0.39	2.67 ± 0.71	0.61	<0.05	12.8	0.081
Transfers	2.98 ± 0.58	3.01 ± 0.81	0.57	<0.05	4.7	0.57
Wheeling on Tile	2.99 ± 1.0	3.62 ± 1.20	0.94	<0.0001	23.5	<0.0001
Laundry	2.49 ± 0.42	3.03 ± 0.92	0.83	0.0004	20.3	<0.05
Rest	1.34 ± 0.31	2.00 ± 0.76	0.71	<0.05	48.4	<0.05

ADL = activity of daily living.

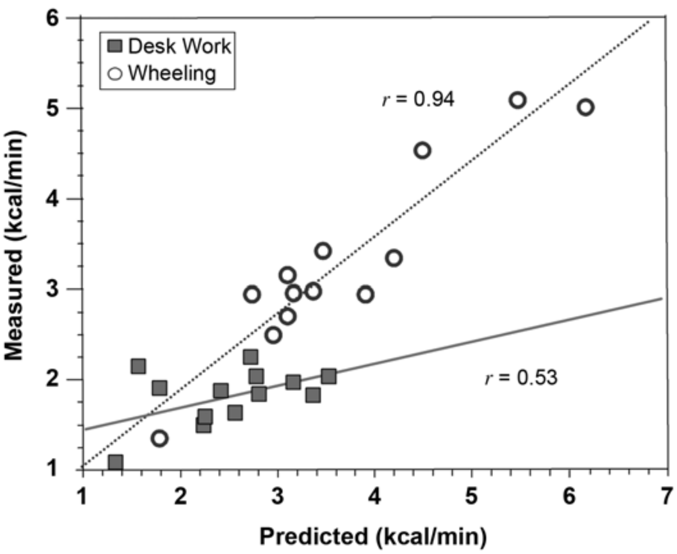

Figure.
Measured vs predicted energy expenditure for two activities of daily living. Plotted lines indicate linear regression; r = Pearson's correlation coefficient.

Table 3.
Pearson's correlation coefficient (r) for predicted and measured energy expenditure by lesion level for activities of daily living and rest.

Activity	Tetraplegia (n = 3)		Paraplegia (n = 10)	
	r	p-Value	r	p-Value
Total Period	0.84	<0.0001	0.78	<0.0001
Desk Work	0.27	0.82	0.57	0.84
Dishes	0.97	0.16	0.62	0.058
Transfers	0.90	0.29	0.43	0.22
Wheeling on Tile	0.99	<0.05	0.95	<0.0001
Laundry	0.94	0.22	0.89	0.0006
Rest	0.38	0.75	0.77	<0.05

Table 4.
Percentage of peak exercise heart rate reached by lesion level during activities of daily living and rest.

Activity	Tetraplegia (n = 3)	Paraplegia (n = 10)	p-Value
Desk Work	81	63	<0.05
Dishes	82	65	<0.05
Transfers	92	68	<0.05
Wheeling on Tile	90	74	0.05
Laundry	85	70	<0.05
Rest	75	61	<0.05

(4) the accuracy of heart rate in predicting energy expenditure is similar between individuals with paraplegia and tetraplegia.

It is reasonable to expect that heart rate monitoring for people with SCI would require individual calibration because estimates from nondisabled subjects consistently overestimate energy expenditure in those with SCI. Although heart rate has been reported to be reproducible in men with SCI during transfers and curb ascent [15] and has been used to estimate energy expenditure in people with SCI [9,16], the validity of this method needs to be further defined because of several complicating factors. First, high variability in energy expenditure exists between different people with SCI [9]. Second, people with SCI are reported to have a lower $\dot{V}O_2$ for a given heart rate [17–19], particularly those with higher level injuries [18]. The relationship between heart rate and $\dot{V}O_2$ during exercise has been reported to be weaker in those with high-level tetraplegia (cervical vertebrae 6 [C6] and above) versus low-level tetraplegia (cervical vertebrae 7 to thoracic vertebrae 1 [C7–T1]) [20]. Decreased muscle mass that affects the maximum achievable $\dot{V}O_2$, disrupted sympathetic nervous system control that affects heart rate, and a decrease in physical capacity to complete the maximum exercise test with an arm ergometer may all contribute to the weaker relationship observed in those with high-level tetraplegia; thus, reducing the usefulness of heart rate to estimate energy expenditure. Although the heart rate-oxygen uptake relationship among people with tetraplegia is not as strong as in those with paraplegia or nondisabled populations, it is nevertheless acceptably high (r = 0.80 for those C6 and above and 0.90 for those with C7–T1 injuries) [20]. In the current study, a similar relationship was observed between heart rate and $\dot{V}O_2$ for people with tetraplegia and paraplegia (r = 0.84 and 0.78, respectively).

Although heart rate alone (without individual calibration) was a statistically significant predictor of energy expenditure in our sample, its clinical application is limited given its ability to explain only 8.3 percent of the variation in energy expenditure. Conversely, when individualized regression equations from the maximum exercise tests were used to convert the heart rate values during various activities to energy expenditure, the variance explained rose to 55 percent for the entire measurement period, including rest. Investigators have used similar methods, such as the heart rate-flex model [21], to improve estimates of energy expenditure among ambulatory subjects. The heart rate-flex method accounts for resting periods in the calibration equation (of heart rate and $\dot{V}O_2$), but a validation study for its use in people with SCI is needed.

Predicted energy expenditure may be more accurate during activities of higher intensity because the prediction equation only includes those heart rates and corresponding energy expenditure values from the maximum exercise test. In the present sample, >90 percent of the energy expenditure during wheeling was explained by the individualized regression equations in all subjects grouped together (98% and 90% for tetraplegia and paraplegia, respectively). Although heart rate from the calibrated equations was a significant predictor of energy expenditure for all the activities except desk work, the variance explained ranged from 28 to 88 percent, depending on the intensity of the activity. In persons with tetraplegia, the regression equations significantly predicted energy expenditure when transferring from the wheelchair to bed, but this was not the case for persons with paraplegia. When the percentage of the participants' maximum heart rate was explored, those with tetraplegia reached a significantly greater percentage of their maximum exercise heart rate during all ADL when compared with that reached by those with paraplegia (**Table 4**). In the group with tetraplegia, the individualized regression equations had relatively poor predictive ability for desk work and rest, which are both sedentary activities.

Heart rate from the predictive equations better estimated energy expenditure than heart rate without individualized equations and explained an additional 47 percent of the variance in the energy expenditure (55% vs 8%). However, energy expenditure estimated with calibrated heart rate from individualized exercise regression equations overestimated the measured energy expenditure for all five ADL and rest, by 5 to 48 percent. Although the predicted energy expenditure for wheeling on tile was strongly associated with measured energy expenditure (r = 0.94), the differences in the energy expenditure values were significantly different, with a 24 percent overestimation. To expend the 150 to 200 kcals in a single exercise session that is recommended for ambulatory individuals [4], people with SCI would be required to exercise for 50 to 67 minutes from measured versus 41 to 55 minutes from estimated energy expenditure; the difference roughly equates to the difference in energy cost between wheeling and doing dishes for the same duration.

Our study has several limitations. First, the study sample size was small, which limited statistical power. The small sample sizes were particularly limiting during subanalyses for differences between paraplegia and tetraplegia. In the latter analyses, the potential exists for a correlation to be influenced by a single outlier. In addition, energy expenditure and heart rate data were not collected under steady state conditions during exercise testing or ADL; the estimates of energy expenditure would likely have been more accurate had $\dot{V}O_2$ been constant. Finally, our estimates of energy expenditure were derived from the entire 5-minute measurement period for each ADL. We did this to better reflect real-life energy costs of each activity and to optimize the stability of the data. However, shorter periods (e.g., the last minute or two of an activity) may have provided a truer reflection of each particular activity.

CONCLUSION

Heart rate monitoring with the use of individually calibrated prediction equations of heart rate and $\dot{V}O_2$ provided gross estimations of energy expenditure in persons with SCI, particularly for higher-intensity activities. Accurate estimates of energy expenditure for people with SCI are needed to help researchers and clinicians monitor programs aimed at meeting the recommendations of public health initiatives for increased physical activity. While these recommendations have well-documented benefits in nondisabled individuals, further studies are needed for people with SCI because they expend less energy during activity and at rest [9]. Accurate estimates of energy expenditure for people with SCI may be useful in making activity recommendations for individuals with SCI for reduction of CVD risk in this population.

REFERENCES

1. Eckel RH. Obesity and heart disease: a statement for healthcare professionals from the Nutrition Committee, American Heart Association. Circulation. 1997;96(9):3248–50.
2. Pearson TA, Blair SN, Daniels SR, Eckel RH, Fair JM, Fortmann SP, Franklin BA, Goldstein LB, Greenland P, Grundy SM, Hong Y, Miller NH, Laurer RM, Ockene IS, Sacco RL, Sallis JF Jr, Stone NJ, Taubert KA. AHA guidelines for primary prevention of cardiovascular disease and stroke: 2002 update. Circulation. 2002;106(3):388–91.
3. American College of Sports Medicine (ACSM). ACSM's guidelines for exercise testing and prescription. 6th ed. Baltimore (MD): Lippincott Williams & Wilkins; 2000.

4. Pate RR, Pratt M, Blair SN, Haskell WL, Macera CA, Bouchard C, Buchner D, Ettinger W, Heath GW, King AC, Kriska A, Leon AS, Marcus BH, Morris J, Paffenbarger RS, Patrick K, Pollock ML, Rippe JM, Sallis J, Wilmore JH. 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.
5. Bauman WA, Adkins RH, Spungen AM, Kemp BJ, Waters RL. The effect of residual neurological deficit on serum lipoproteins in individuals with spinal cord injury. Spinal Cord. 1998;36(1):13–17.
6. Hoffman MD. Cardiorespiratory fitness and training in quadriplegics and paraplegics. Sports Med. 1986:3(5):312–30.
7. Collins E, Langbein WE, Williams KJ, Bammert C, Nemchausky BA. Energy expenditure compendium of physical activities in persons with spinal cord injury [abstract]. J Spinal Cord Med. 2003;26(3):294.
8. Cox SA, Weiss SM, Posuniak EA, Worthington P, Piroleau M, Heffley G. Energy expenditure after spinal cord injury: an evaluation of stable rehabilitating patients. J Trauma. 1985;25(5):419–23.
9. Mollinger LA, Spurr GB, El Ghatit AZ, Barboriak JJ, Rooney CB, Davidoff DD, Bongard RD. Daily energy expenditure and basal metabolic rates of patients with spinal cord injury. Arch Phys Med Rehabil. 1985;66(7):420–26.
10. Borg G. Borg's perceived exertion and pain scales. Champaign (IL): Human Kinetics; 1998.
11. Duffield R, Dawson B, Pinnington HC, Wong P. Accuracy and reliability of a COSMED K4b^2 portable gas analysis system. J Sci Med Sport. 2004;7(1):11–22.
12. Forkink A, Frings-Dresen MH. Measurement of oxygen consumption with the COSMED K2: a comparative study. Appl Ergon. 1994;25(2):95–100.
13. Maiolo C, Melchiorri G, Iacopino L, Masala S, De Lorenzo A. Physical activity energy expenditure measured using a portable telemetric device in comparison with a mass spectrometer. Br J Sports Med. 2003;37(5):445–47.
14. Eisenman JC, Brisko N, Shadrick D, Welsh S. Comparative analysis of the COSMED Quark b^2 and K4b^2 gas analysis systems during submaximal exercise. J Sports Med Phys Fitness. 2003;43(2):150–55.
15. Janssen TW, Van Oers CA, Van der Woude LH, Hollander AP. Reliability of heart rate responses to non-steady-state activities of daily living in men with spinal cord injuries. Scand J Rehabil Med. 1994;26(2):71–78.
16. Yamasaki M, Irizawa M, Komura T, Kikuchi K, Sasaki H, Kai K, Odoko K. Daily energy expenditure in active and inactive persons with spinal cord injury. J Hum Ergol (Tokyo). 1992;21(2):125–33.
17. Hjeltnes N. Oxygen uptake and cardiac output in graded arm exercise in paraplegics with low level spinal lesions. Scand J Rehabil Med. 1977;9(3):107–13.
18. Irizawa M, Yamasaki M, Muraki S, Komura T, Seki K, Kikuchi K. Relationship between heart rate and oxygen uptake during submaximal arm cranking in paraplegics and quadriplegics. Ann Physiol Anthropol. 1994;13(5):275–80.
19. Jehl JL, Gandmontagne M, Pastene G, Eyssette M, Flandrois R, Coudert J. Cardiac output during exercise in paraplegic subjects. Eur J Appl Physiol Occup Physiol. 1991; 62(4):256–60.
20. McLean KP, Jones PP, Skinner JS. Exercise prescription for sitting and supine exercise in subjects with quadriplegia. Med Sci Sports Exerc. 1995;27(1):15–21.
21. Strath SJ, Bassett DR Jr, Thompson DL, Swartz AM. Validity of simultaneous heart rate-motion sensor technique for measuring energy expenditure. Med Sci Sports Exerc. 2002;34(5):888–94.

Submitted for publication December 1, 2004. Accepted in revised form May 6, 2005.