Use of Heart Rate to Predict Energy Expenditure from Low to High Activity Levels

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Abstract

This study evaluated the ability to use the relationship between heart rate (HR) and oxygen uptake ($\dot{V}O_2$) to estimate energy expenditure (EE) from low to high physical activity with different HR-based prediction equations. General prediction equations were established based on the individual relations between HR and EE. Possibilities to improve the EE estimation with using alternatives for respective HR were also assessed. The alternatives were % of HR reserve: 100 × [(activity HR - resting HR)/(maximal HR - resting HR)], (HRR), and the difference between activity HR and resting HR (activity HR - resting HR), (HRnet). Forty-two men (age mean 36.5 [sd 7.6] y, BMI 24.5 [2.4] kg × m^{-2}, $\dot{V}O_2$max 45.2 [6.5]) kg × ml × min^{-1} and 47 women (mean age 37.5 [9.5], BMI 23.3 [3.4], $\dot{V}O_2$max 36.3 [5.4]) performed an exercise test consisting of physically low-activity tasks and a maximal treadmill uphill walking test. Respiratory gases were obtained from indirect calorimetry. HR was registered by electrocardiography and EE was calculated from ($\dot{V}O_2$) and carbon dioxide ($\dot{V}CO_2$) production. Generalised linear models with random effects were used for the prediction of EE. EE values of the tests (one value at each intensity level) were predicted in separate models by the respective HR, HRR or HRnet values. The other predictors used in all models were body weight, sex and the intensity of exercise. The standard error of estimate (SEE) was 1.41 kcal × min^{-1} (5.89 kJ) in the model with HR variable as a predictor, 1.01 kcal × min^{-1} (4.22 kJ) with HRR variable, and 1.08 (4.51 kJ) with HRnet variable. The results show that the prediction of EE is more accurate if HRR or HRnet are used in prediction equation instead of HR.

Key words
Energy expenditure · prediction equation · physical activity · exercise · heart rate reserve · free-living energy expenditure

Introduction

Physical activity has important benefits in maintaining good health and in preventing chronic diseases, such as coronary heart disease and diabetes mellitus. Recommendations for suitable quantities of physical activity for health benefits for the general population have also been given based on cumulative or total energy expenditure (EE) of activity, per day or per week [21]. We now need to find a suitable field method to obtain reliable information on physical activity (PA) or energy expenditure (EE) from daily activities, as well as develop practical tools for assessing the amount of PA.

The assessment of PA or EE in free-living humans can be done with a variety of methods. The doubly-labelled water method [24] is accurate but expensive. The telemetric system for oxygen uptake ($\dot{V}O_2$) measurements [6] can be used in field situations but is not a valid method for daily use. Motion sensors [22] and accelometers [17] are easy to use, but the validity of the methods varies [22, 18, 2, 7, 5]. Different kinds of recall questionnaries, exercise logs and diaries [23] have also been developed and used in research settings.

In addition to the above-mentioned methods the relationship between HR and $\dot{V}O_2$, which reflects EE, provides a promising method for predicting EE. The relationship seems to be linear

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during dynamic muscle work up to about 85% of the individual maximal HR, after which point the relationship turns unlinear [19,12]. HR recording is a feasible, reasonably priced and accurate method due to the new technology of portable HR monitors . In earlier studies, various models have been applied when using HR data as an estimate of EE. It has been found that individual HR- $\dot{V}O_2$ calibration curves performed in the laboratory are the most accurate way to predict EE [1,20,3,15]. Mean heart rate [20] and the difference between activity HR and resting HR (HRnet) [23] have also been used as models for assessing EE in the field.

The greatest limitation for calculating EE during the whole day, however, is the almost flat slope of the HR- $\dot{V}O_2$ relationship at low activity levels [14].

It is possible to use a general equation to estimate EE at low activity levels [26], but the estimate is inaccurate. Individual regression equations for daily EE can be calculated from laboratory measurements where $\dot{V}O_2$ and HR are measured during physical activity with the intensity increasing gradually from very low to strenuous levels [19,13]. Prediction equations for EE are usually calculated separately for light activity and for strenuous dynamic muscle work. The HR (beats per min) which is the cut-off point between the two activity levels is called "flex HR". It has been shown that the HR at the flex point is usually between 80 and 100 bpm [19].

In our earlier study we developed general prediction equations to predict exercise-induced EE separately for men and women from individual relationships between HR and $\dot{V}O_2$ during incremental walking and cycling exercise [8]. The aim of the present study was to develop an equation to predict free-living EE. The equation was based on HR and other individual factors (e.g. body weight, gender and age) from low EE to strenuous physical activity. Of special interest was to compare the predictive value of different HR variables, HR, % of HR reserve: 100 × [(activity HR - resting HR)/(maximal HR - resting HR)], (HRR) [10] and the difference between activity HR and resting HR (activity HR - resting HR), (HRnet).

Material and Methods

Subjects

Altogether 93 participants from four different work sites volunteered in this study. Two subjects were excluded due to technical problems during the test and two due to ECG abnormalities. The final study group consisted of 89 healthy volunteers, 42 men (19 – 51 y) and 47 women (21 – 53 y). Their physical characteristics are presented in Table **1**. A written informed consent was obtained from all the participants. None of the subjects were competitive athletes or used regular medication. The study was approved by an independent research ethics committee of the UKK Institute.

Measurements

The subjects were asked to refrain from alcohol use or strenuous physical activity for 24 h before laboratory measurements and from eating or using caffeine during the 3 h preceding the test.

Table **1** Physical characteristics of the men and women

	Men (n = 42) Mean (SD)	*Women (n = 47) Mean (SD)*
Age (y)	36.5(7.6)	37.5(9.5)
BMI ($kg \times m^{-2}$)	24.5(2.4)	23.3(3.4)
$\dot{V}O_2max$ ($ml \times kg^{-1} \times min^{-1}$)	45.2(6.5)	36.3(5.4)

Body weight and height in light clothing were measured before the test session using standard techniques.

The first part of the test session was a 28-min light activity protocol, aimed at 1 – 3 metabolic equivalents (MET). The basis for the METs (1 MET) was obtained from respiratory gases measured during a 4-min rest while the subject was sitting peacefully. That was followed by a light activity test session during which subjects moved three items at a fixed rate: a notebook, a 1 kg- and a 2 kg-weight between four tables of differing heights, first for 4 min in a sitting position and then for 4 min in a standing position. During the first two 4-min periods the subjects moved the items at the rate of 40 times per minute, then the speed was increased for the next 8 min to 60 times per minute and for the last 8 min to 80 times per minute.

After the light activity measurements the subject was allowed to take a short break and drink some water. The second part of the test consisted of a maximal treadmill (Lasset, Telineyhtymä, Finland, 1986) uphill walking test, lasting 13 – 22 min individually. The protocol for the maximal walking test was chosen according to individually predicted fitness levels [9]. A 4-min warm-up was followed by 3-min incremental work loads (theoretical increase in oxygen uptake 3 – 6 $ml \times kg^{-1} \times min^{-1}$ for each workload) up to volitional exhaustion.

Oxygen uptake ($\dot{V}O_2$ $l \times min^{-1}$) and carbon dioxide production ($\dot{V}CO_2$ $l \times min^{-1}$) were calculated from the respiratory gas analysis by an indirect calorimeter (Sensor Medics Vmax, California, USA). EE ($kcal \times min^{-1}$) was calculated over the last two minutes of each of the seven light activity protocol stages, over the 4-min warm-up, and from the last minute of each 3-min stage during the incremental walking test by the equation of Weir [24]: EE ($kcal \times min^{-1}$) = 3.941 × $\dot{V}O_2$ ($l \times min^{-1}$) + 1.106 × $\dot{V}CO_2$ ($l \times min^{-1}$). Heart rate (HR, bpm) was monitored and registered by ECG (Max-1, Marquette Electronics, Milwaukee, USA).

Statistical analysis

Generalised linear models with random effects were used for predicting EE [4]. Twenty-one EE values of the test sessions (last two values from each light activity protocol and one value from each stage during the walking test) were predicted in separate models by the respective HR values, HRR values [10] and HRnet values in the same test. Body weight and age as continuous variables, and sex (0 = female, 1 = male) and test level (0 = light activity, 1 = high activity) as dichotomous variables were included as predictors into the models. At first, all predictive variables and their two-, three- and four-way interactions were entered into

Table **2** Estimated regression coefficients for predicting the activity energy expenditure (n = 89) by three different models

Term[a]	Model 1 β[b]	Model 1 SE (β)[c]	Model 1 p-value	Model 2 β[b]	Model 2 SE (β)[c]	Model 2 p-value	Model 3 β[b]	Model 3 SE (β)[c]	Model 3 p-value
Constant	−4.70	1.63	0.004	0.74	0.68	0.27	0.84	0.67	0.21
HR	0.045 [d]	0.017	0.007	0.022 [e]	0.024	0.36	0.011 [f]	0.022	0.62
Weight (kg)	0.0019	0.0247	0.94	0.0070	0.0103	0.50	0.0054	0.0103	0.60
Sex (0 = female, 1 = male)	9.26	2.76	< 0.001	−0.30	1.19	0.80	−0.40	1.18	0.73
Activity level (0 = low, 1 = high)	−1.22	0.27	< 0.001	−0.58	0.50	0.25	−0.73	0.51	0.15
HR.Weight	0.00052 [d]	0.00025	0.039	0.00102 [e]	0.00036	0.005	0.00106 [f]	0.00033	0.001
HR.Sex	−0.071 [d]	0.028	0.011	0.041 [e]	0.044	0.35	0.010 [f]	0.038	0.79
HR.Activity	0.013 [d]	0.002	< 0.001	0.047 [e]	0.016	0.004	0.049 [f]	0.015	0.002
Weight.Sex	−0.152	0.037	< 0.001	0.0004	0.0159	0.98	0.0021	0.0158	0.90
Weight.Activity	0.015	0.003	< 0.001	0.020	0.008	0.012	0.022	0.008	0.005
Sex.Activity	0.215	0.084	0.010	1.17	0.81	0.15	1.30	0.81	0.11
HR.Weight.Sex	0.00137 [d]	0.00038	< 0.001	−0.00002 [e]	0.00058	0.97	0.00016 [f]	0.00051	0.75
HR.Weight.Activity				−0.00052 [e]	0.00025	0.039	−0.00057 [f]	0.00024	0.015
HR.Sex.Activity				−0.085 [e]	0.032	0.008	−0.085 [f]	0.027	0.002
Weight.Sex.Activity				−0.016	0.011	0.14	−0.018	0.011	0.099
HR.Weight.Sex.Activity				0.00129 [e]	0.00042	0.002	0.00127 [f]	0.00037	< 0.001
SEE =	1.41 kcal × min^{-1} (5.89 kJ × min^{-1})			1.01 kcal × min^{-1} (4.22 kJ × min^{-1})			1.08 kcal × min^{-1} (4.51 kJ × min^{-1})		

[a] Full stop denotes interaction between two variables.
[b] Estimate of regression coefficient.
[c] Asymptotic standard error of the coefficient.
[d] HR = heart rate (beats/min).
[e] HR = 100 × (heart rate − resting heart rate)/(maximum heart rate − resting heart rate).
[f] HR = heart rate − resting heart rate.

the model. The backward selection method with the Wald test statistic as the removal criterion ($p > 0.10$) was then used to delete the nonsignificant terms from the model. The goodness-of-fit of the different models was compared by the means of log-likelihood statistics.

Results

Individual METs were calculated based on respiratory gases measured during the 4-min rest before the activity measurements. During the light activity the mean METs were under 3. During the incremental walking test, the mean METs increased up to 10.

Three different HR variables were used in the prediction models of energy expenditure: HR (bpm) in model 1, HRR in model 2 and HRnet in model 3. Other predictors used in all models were body weight, gender, age and test level. Age and its interaction with other predictors did not improve statistically significantly the goodness-of-fit of any models, and age was therefore excluded from the final models. Regression coefficients of the best models are presented in Table **2** and the corresponding regression line for model 1 in Fig. **1**. Equations in Table **2** are also be presented separately for men and women at different activity levels as follows:

Predicted EE (kcal × min^{-1}):

Model 1
Women
Low activity level: −4.70 + 0.0449 (HR) – 0.0019 (weight) + 0.00052 (HR) (weight)
High activity level: −5.92 + 0.0577 (HR) – 0.0167 (weight) + 0.00052 (HR) (weight)

Men
Low activity level: 4.56 – 0.0265 (HR) – 0.1506 (weight) + 0.00189 (HR) (weight)
High activity level: 3.56 – 0.0138 (HR) – 0.1358 (weight) + 0.00189 (HR) (weight)

Model 2
Women
Low activity level: 0.744 + 0.0216 (HRR) + 0.00699 (weight) + 0.00102 (HRR) (weight)
High activity level: 0.165 + 0.0688 (HRR) + 0.02666 (weight) + 0.00050 (HRR) (weight)

Men
Low activity level: 0.449 + 0.0627 (HRR) + 0.00743 (weight) + 0.00100 (HRR) (weight)
High activity level: 1.044 + 0.0250 (HRR) + 0.01088 (weight) + 0.00177 (HRR) (weight)

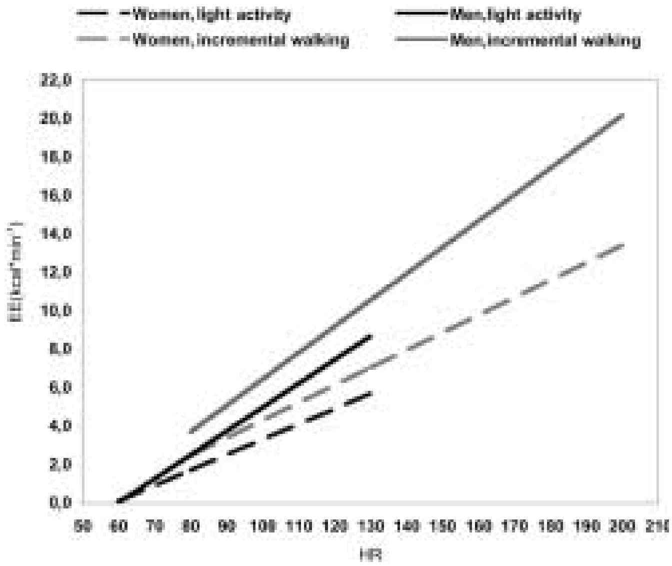

Fig. 1 Model 1: heart rate, sex, body weight and test level against 21 energy expenditure values regressions at mean body weight for men (79.9 kg) and women (64.9 kg).

Model 3
Women
Low activity level: 0.842 + 0.0107 (HRnet) + 0.00544 (weight) + 0.00106 (HRnet) (weight)
High activity level: 0.113 + 0.0596 (HRnet)+ 0.02761(weight) + 0.00049 (HRnet) (weight)

Men
Low activity level: 0.438 + 0.0210 (HRnet) + 0.00750 (weight) + 0.00122 (HRnet) (weight)
High activity level: 1.012 – 0.0154 (HRnet) + 0.01140 (weight) + 0.00192 (HRnet) (weight)

The plots of the residuals (predicted – observed values) against the observed EE values are presented in Figs. **2 a-c**. The standard error of estimate (SEE) was smallest, 1.01 kcal × min^{-1} (4.22 kJ), in model 2, which included HRR, body weight, sex and test level as predictors (Fig. **2 a**). SEE was 1.08 kcal × min^{-1} (4.51 kJ) in the model with HRnet, body weight, sex and test level as predictors (Fig. **2 b**) and 1.41 kcal × min^{-1} (5.89 kJ) in the model with HR, body weight, sex and test level as predictors (Fig. **2 c**).

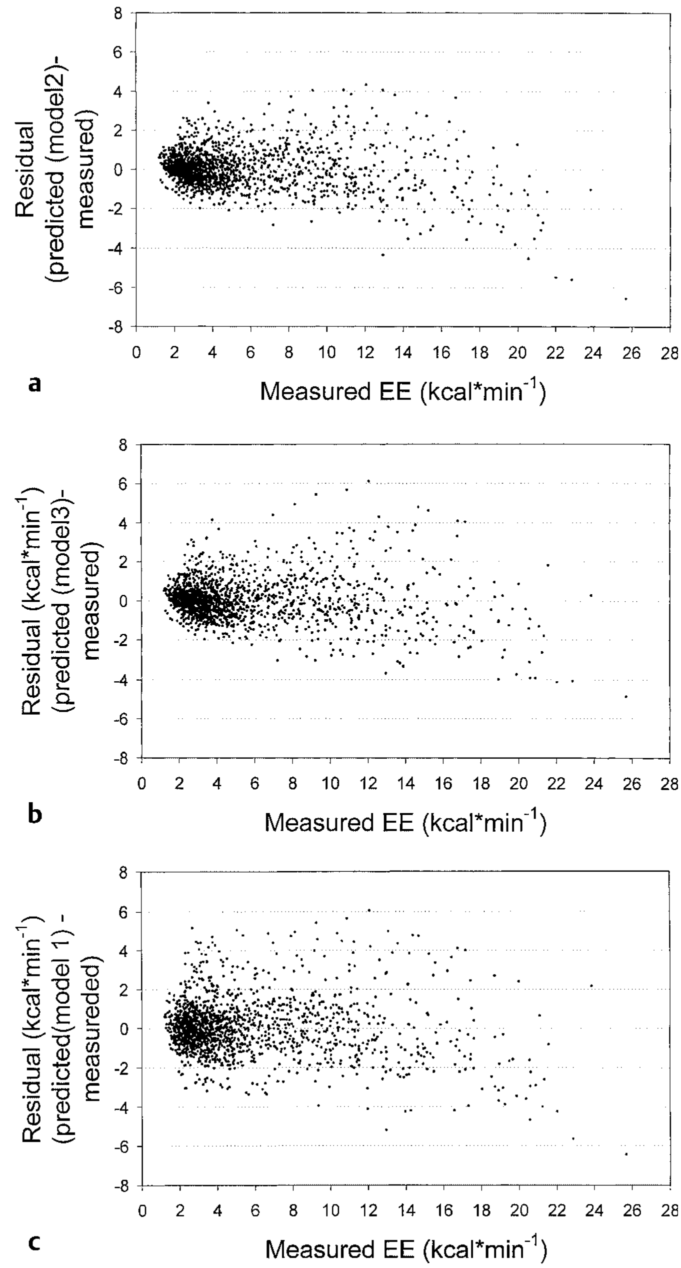

Fig. 2 The plots of the residuals (predicted – measured values) against the measured EE values. **a** Model 2 (HRR, sex, body weight and test level) SEE = 1.01 kcal. **b** Model 3 (Hrnet, sex, body weight and test level) SEE = 1.08 kcal. **c** Model 1 (HR, sex body weight and test level) SEE = 1.41 kcal.

Discussion

It seems that our test protocol covers a wide range of daily activity levels. Mean METs during the light activity test session were under 3 METs and increased during uphill walking to 10 METs.

In our previous study [8] we concluded that at least sex and body weight should be included in the model for predicting EE based on HR during physical activity. In this study the aim was to develop a prediction equation from low to strenuous activity levels using the similar principle. The results of our study show that both body weight and sex are still valuable factors in the prediction equation of EE. The significance of sex is based on the difference of fat-free mass between men and women. It is generally known that men have more fat-free mass than women, which results in higher EE during the same exercise [16]. An increase in body weight increases EE during physical activity, and therefore, body weight should also be included in the models.

Against the general view of the relationship between HR and EE being almost flat at low EE levels [14], the relationship between HR and EE in our study was almost similar during physically light activities and during incremental walking. The test level, describing the intensity of activity, was a significant factor in this study. During light activities, while smaller muscle groups were working, mean EE (at mean body weight) at the same HR (bpm) was lower than the EE of incremental walking. During the light activity test session the work was done mostly with the upper body. Upper body work will raise the heart rate, but the cardiac output will remain lower than when using larger muscle groups during incremental walking [16.].

In this study we were especially interested in studying the predictive value of different HR variables (HR, HRR and HRnet). The results show that the prediction of EE gets more accurate if HRR or HRnet are used in the equation. The HRR method is based on the difference between resting and maximal heart rate. It describes the individual HR capacity and is often used to describe the optimal training level [10]. The resting HR is lower in fit subjects, and the training status affects the relationship between HR and EE. With HRnet we can take that into account and improve the accuracy of the equation.

HR is a simple physiological function to measure because of the new technology of HR recording equipment (Polar Electro Oy, Kempele, Finland). The findings in this study support the belief that HR recording may be a valid method to assess EE in field settings [14]. Our results show that generalised EE prediction equations developed in this study are possible to present for adult men and women.

In our next study we will validate prediction equations developed in this study in an independent subject group.

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