Estimation Of Oxygen Consumption Based on Exercise Patterns for People with Type 1 Diabetes

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Introduction

During physical activity, whole body oxygen consumption may increase as much as 20-fold. For people with Type 1 Diabetes, information on the aerobic energy expenditure during the exercise may help patients to make adjustments for infused insulin rate or decide the amount of carbohydrate intake avoiding the low blood glucose level. Direct determination of oxygen consumption is not always feasible. A model for estimating oxygen consumption is proposed for two common types of aerobic exercise (treadmill and stationary bicycle) over a wide range of exercise intensities and durations based on exercise conditions such as speed, grade and resistance.

Materials and Methods

Eleven young adults with type 1 diabetes participated in exercise studies at the University of Illinois at Chicago (UIC). The time and the duration of their participation and exercise were flexible and varied between 3-6 days from morning to evening. Each subject performed 4 to 6 exercise sessions of moderate to high intensity exercise with 30-40 minutes duration. On the first day, the Maximal Oxygen Consumption test (VO_2 max) was performed to assess aerobic (cardiovascular) fitness using a Bruce protocol. In this protocol, the treadmill speed and grade are increased together to specified endpoints (e.g., exhaustion). Figure1 demonstrates the change of speed (mph) and grade (tangent of slope × 100) during the exercise test.

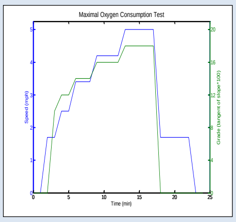


Figure 1. Exercise profile for Maximal Oxygen Consumption test.

Figure 2. Zephyr Bioharness chestband measures heart rate.

Oxygen consumption ($L.min^{-1}$) during the maximal exercise stress test is continuously determined using data from an air volume meter and measuring O_2 and CO_2 fractions in inhaled and exhaled gases. Estimated of the energy expenditure (EE) also can be stated by metabolic equivalent (MET) units where 1 MET is assumed to be assumed to be 3.5 ml/min/kg resting oxygen consumption. EE in MET unit is also computed from test data. Heart rate can be reliably monitored and recorded by non-invasive sensors (Fig. 2). We used recorded EE, heart rate and exercise specification to build a model which estimates aerobic EE (i.e. metabolic equivalent).

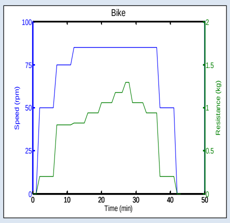


Figure 3.
Bike exercise protocol.

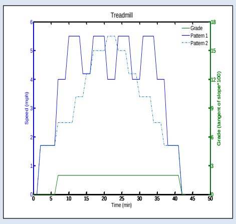
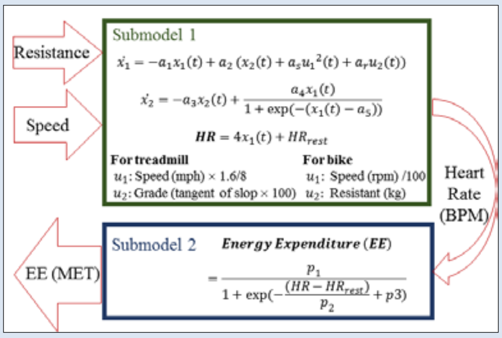


Figure 4.
Treadmill exercise protocols.

In addition to Maximal Oxygen Consumption test, each subject performed two treadmill and two bike workouts. The exercise specification in terms of change of speed and resistance for the two bike sessions are almost the same (Fig. 3 shows one session), and the speed patterns are different for the treadmill sessions (Fig. 4).

The model estimating the energy expenditure for these two types of aerobic exercise consists of two submodels: a cardiovascular submodel and an energy expenditure submodel. The former describes heart rate values based on time, type and intensity of exercise. The latter calculates aerobic energy expenditure during these exercises and recovery time based on heart rate (Figure 5).



Submodel 1

$$\dot{x}_1 = -a_1 x_1(t) + a_2\left(x_2(t) + a_s {u_1}^2(t) + a_r u_2(t)\right)$$

$$\dot{x}_2 = -a_3 x_2(t) + \frac{a_4 x_1(t)}{1 + \exp(-(x_1(t) - a_5))}$$

$$HR = 4x_1(t) + HR_{rest}$$

For treadmill
u_1: Speed (mph) × 1.6/8
u_2: Grade (tangent of slop × 100)

For bike
u_1: Speed (rpm) /100
u_2: Resistant (kg)

Submodel 2

$$\textit{Energy Expenditure (EE)} = \frac{p_1}{1 + \exp\left(-\frac{(HR - HR_{rest})}{p_2} + p3\right)}$$

Figure 5. Cardiovascular and energy expenditure submodels.

Validation and Results

Submodel 1 is an extension of a nonlinear model [1] where the treadmill speed is the only input. However, changes in the grade of the treadmill affects heart rate and energy expenditure remarkably. Thus, we added u_2 the grade of treadmill as the second input to submodel 1. Parameters a_s and a_r as the coefficients of inputs are new parameters added to the model. a_1 to a_5 are the parameters of the original model. Among the seven parameters of submodel 1, a_2, a_5, a_s and a_r are the four person-specific parameters while a_1, a_3 and a_4 are the same for all subjects.

Training data sets are stress test and one of the treadmill sessions. The second treadmill session is testing data. The parameters are computed by minimizing the Mean Square Error (MSE) over training data sets by MATLAB (fminsearch) optimization. Submodel 1 is also able to estimate heart rate for stationary bike when the inputs are cycling speed and resistance. For cycling, the values of parameters are different from treadmill and are found by optimization over one of bike data set. The estimated heart rates by using submodel 1 are shown in Figure 5 and 6 for treadmill and bike respectively.

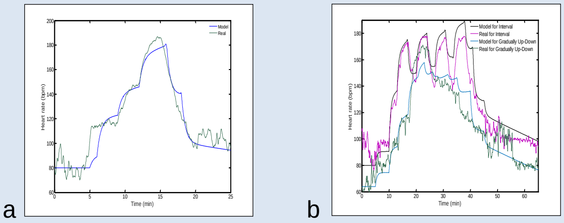


Figure 6. Treadmill (a) stress test, (b) Oscillatory pattern is Interval training (MSE=119) and testing data set (MSE=106).

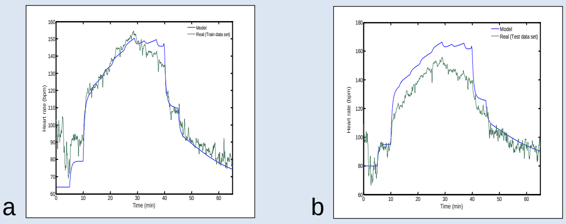


Figure 7. Cycling (a) training (MSE=88) (b) testing (MSE=138).

Submodel 2 estimates energy expenditure (EE) in MET units based on heart rate while the constraint $EE(HR_{rest})=1$ is enforced. MATLAB non-linear least squares fitting calculates parameters (p_1, p_2, p_3). Figure 8 shows the estimated EE (output of submodel 2) vs. estimated heart rate (output of submodel 1) and compares it with the measured EE vs. measured heart rate during Maximal Oxygen Consumption test. Figure 9 shows the output of consecutive submodels by comparing estimated energy expenditure for 12 minutes of stress test.

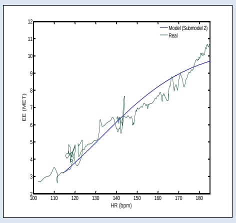


Figure 8. Estimated EE vs. estimated heart rate.

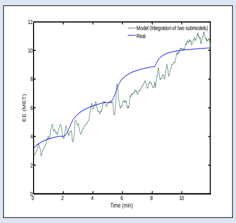


Figure 9. Estimated EE for 12 minutes of stress test.

Conclusions

The model provides a good estimate of energy expenditure based on time and intensity of aerobic exercise for people with T1D. Submodel 1 is able to track heart rate experimental data despite frequent changes of the speed and resistance in exercise protocol. Investigation of different exercise protocols enables building a more general heart rate estimation model.

While oxygen consumption is frequently described by a linear function of heart rate during exercise, the functionality is not linear around minimum and maximum heart rate. Submodel 2 appropriately captures the functionality of oxygen consumption (i.e. aerobic EE) over wide ranges of heart rate.

References

[1] TM Cheng, AV Savkin, BG Celler, SW Su, L Wang, Nonlinear modeling and control of human heart rate response during exercise with various work load intensities, *IEEE Trans. Biomed. Eng.*, 55: 2499–2508, 2008