On- and Off Dynamics and Respiration Rate Enhance the Accuracy of Heart Rate Based VO_2 Estimation

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Current heart rate (HR) based calculations use linear steady state based function to calculate VO_2 from HR. HR to VO_2 relationship changes during variations in exercise intensity and non-exercise related physiological processes affecting HR especially at low intensity. **PURPOSE**: To examine whether addition of On- and Off- VO_2-dynamics ($VO_{2HR+ON/OFF}$) and respiration rate ($VO_{2HR+Resp}$) or both ($VO_{2HR+Resp+ON/OFF}$) increase the accuracy of HR based VO_2 estimation (VO_{2HR}). **METHODS**: Beat-by-beat HR and breath-by-breath VO_2 data from 16 male and 16 female healthy untrained adults (age of 38±9 years, weight 70±11 kg, height 172±8 cm and VO_{2max} 44±9 ml/kg•min^{-1}) were collected 5 minutes prior to and 15 minutes after 10-min exercises at 40% and 70% VO_{2max} and maximal stepwise test on bicycle ergometer. Two 50 min series of simulated low intensity real life tasks (RLT, mean HR 101±8 and 105±9 bpm) were also carried out. On- and Off- VO_2 changes were used to model VO_2 dynamics. Four neural network models were constructed using 3% from the data in the learning process: VO_{2HR}, $VO_{2HR+Resp}$, $VO_{2HR+ON/OFF}$, $VO_{2HR+Resp+ON/OFF}$. The whole dataset was used to evaluate the accuracy of the methods using mean absolute error (MAE) between estimated and measured VO_2. **RESULTS**: Accuracy was enhanced (p<.001) in all exercise conditions and during RLTs when ON/OFF-response information was included. Across all subjects and conditions MAE of VO_{2HR} 3.7 ml/kg•min^{-1} was reduced to 3.3, 2.3 and 1.9 ml/kg*min^{-1} improving the accuracy by 11%, 38% and 48% using $VO_{2HR+Resp}$, $VO_{2HR+ON/OFF}$, $VO_{2HR+Resp+ON/OFF}$ methods, respectively. During maximal exercise test MAE of VO_{2HR} 4.9 ml/kg*min^{-1} was reduced to 4.4, 1.8 and 1.3 ml/kg•min^{-1} improving the accuracy by 6.1%, 60.9% and 70.7% using $VO_{2HR+Resp}$, $VO_{2HR+ON/OFF}$, $VO_{2HR+Resp+ON/OFF}$ methods, respectively. **CONCLUSIONS**: Both On- and Off- dynamics and respiration were able to enhance the accuracy of VO_2 estimation compared with VO_{2HR} from maximal to varying low intensity exercise. The greatest and the most consistent improvements were due to On- and Off-dynamics.

INTRODUCTION

Heart rate (HR) recording is the most commonly used method to estimate oxygen (VO_2) and energy consumption in field. HR to VO_2 relationship is unambiguous during steady state at moderate intensity but may be considerably different especially during dynamically changing exercise intensity and due to psychological factors affecting HR at low intensity exercise.

The purpose of this study was to examine whether information on On- and Off- dynamics and respiration rate can increase the accuracy of HR based VO_2 estimation during dynamic changes in exercise intensity and during low intensity exercise.

METHODS

Subjects were 32 healthy adults (16 males, 16 females), age 38±9 years (mean±SD), weight 69.6±10.8 kg, height 171.6±8.5 cm and VO_{2max} 44.0±8.8 ml/kg•min^{-1}. Submaximal steady state and maximal incremental bicycle ergometer (Ergoline, Bitz, Germany) exercises and real life tasks (RLT) were carried out during two different days separated by 1-2 weeks (Figure 1). RLT's included simulated low intensity household, recreational and occupational tasks, such as: sweeping the floor; walking; walking in stairs; carrying load; pushing shopping wheels; lifting and moving light weights; computer tasks and free standing and sitting.

HR-data was collected with rr-recorder (Polar Electro Oy, Kempele, Finland). During bicycle ergometer exercises VO_2 data was collected breath-by-breath using Vmax (Sensor Medics, California, Palo Alto, USA) and during RLT's using portable Cosmed K4 analyzer (S.r.I, Italy). Specialized heartbeat analysis software (Firstbeat Technologies Oy., Jyväskylä, Finland) was used to perform heartbeat analysis.

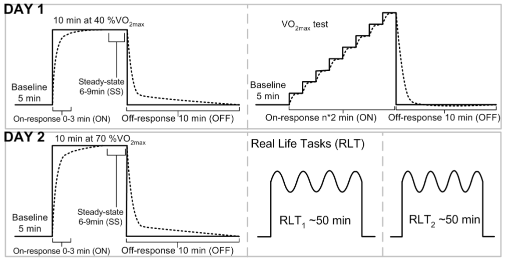

Figure 1. The procedure

Randomly selected data sample representing three percent from the total dataset was used to construct four different neural network (NN) models to estimate second-by-second VO_2:

(1) from HR only (VO_{2HR}),
(2) from HR and respiration rate ($VO_{2HR+Resp}$),
(3) from HR, respiration rate and On- and Off- VO_2 dynamics ($VO_{2HR+Resp+ON/OFF}$) and
(4) from HR and information on On- and Off- VO_2 dynamics ($VO_{2HR+ON/OFF}$).

VO_2, HR and Resp used in the NN modeling were scaled according to the respective individual measured maximum.

The accuracy of the estimates was evaluated using whole dataset (100%) by mean absolute errors (MAE) and error in percent (%-error) between the measured and estimated values. Paired t-test was used to examine whether accuracy was improved using $VO_{2HR+Resp}$, $VO_{2HR+ON/OFF}$ or $VO_{2HR+Resp+ON/OFF}$ –method compared with the VO_{2HR} -method.

RESULTS

VO_2 & HR kinetics

HR to VO_2 relationship had different patterns during On- and Off-responses in 40%, 70% and VO_{2max} test conditions (Figure 2). HR and VO_2 drifted to higher level during 70% bicycle exercise (Table 1).

VO_2 estimation

Including all bicycle and real life task conditions, MAE between the measured and estimated VO_2 was 3.7, 3.3, 2.3 and 1.9 ml/kg/min using VO_{2HR}, $VO_{2HR+Resp}$, $VO_{2HR+ON/OFF}$ and $VO_{2HR+Resp+ON/OFF}$ –method, respectively. Compared with VO_{2HR}, error was reduced by 11 %, 38 % and 48 % with $VO_{2HR+Resp}$, $VO_{2HR+ON/OFF}$ and $VO_{2HR+Resp+ON/OFF}$, respectively. (Figure 3.) In each of the different bicycle and real life task conditions, $VO_{2HR+ON/OFF}$ and $VO_{2HR+Resp+ON/OFF}$ increased the accuracy of VO_2 estimation highly significantly, whereas $VO_{2HR+Resp}$ mostly only during maximal test conditions and RLT_2 (Table 2).

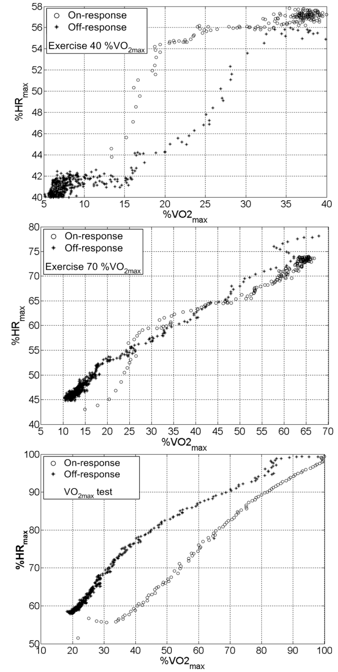

Figure 2. On- and off- responses of VO_2 and HR during bicycle ergometer exercises.

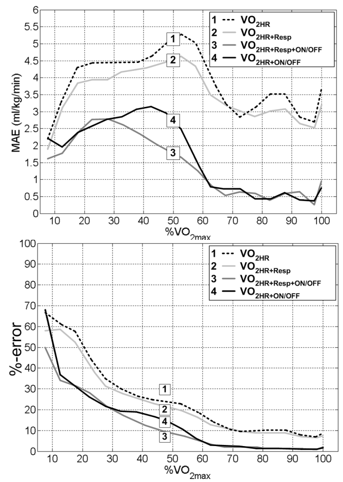

Figure 3. MAE (TOP) and %-error (BOTTOM) of VO_2 estimation methods across all intensities.

Table 1. HR (bpm) and VO_2 (ml/kg•min^{-1}) drift bicycle exercises.

Time	**40 %** (n=23)		**70 %** (n=22)	
	VO_2	HR	VO_2	HR
3rd min	17.0±3.7	104±8	28.6±6.0	135±9
9th min	17.1±3.7	106±9	29.9±6.4***	144±10***

*** p<0.001 different form 3rd min.

Table 2. MAE and %-increase in accuracy compared to VO_{2HR}.

Exercise condition		VO_2 (ml/kg/min)	**MAE VO2 (ml/kg•min^{-1})**				**% increase in accuracy**		
			VO_{2HR}	$VO_{2HR+Resp}$	$VO_{2HR+ON/OFF}$	$VO_{2HR+Resp+ON/OFF}$	$VO_{2HR+Resp}$	$VO_{2HR+ON/OFF}$	$VO_{2HR+Resp+ON/OFF}$
40% n=23	ON	14.9±3.0	3.7±1.3	3.8±1.7	2.7±1.1***	2.1±1.0***	-2±21	17±50	38±27
	OFF	3.4±0.8	2.6±1.4	2.3±0.8	2.3±1.2***	2.0±0.6**	1±33	11±12	15±24
	SS	17.0±3.6	3.5±1.6	3.5±1.8	1.3±0.7***	1.4±1.0***	-4±43	58±20	61±22
70% n=22	ON	23.5±4.8	3.8±1.6	3.4±1.5	2.0±0.7**	1.5±0.4***	5±30	42±27	53±19
	OFF	4.8±0.9	4.5±2.3	3.9±1.8	2.7±1.1***	2.0±0.8***	7±28	32±33	46±28
	SS	29.8±6.0	3.3±2.0	2.8±1.6	0.9±1.2***	0.8±0.6***	6±38	68±30	71±18
Max n=28	ON	27.0±4.5	3.1±1.1	2.6±0.9***	1.3±0.4***	0.9±0.2***	13±13	57±11	68±10
	OFF	9.0±2.3	9.0±3.8	8.3±2.8*	2.6±1.0***	1.7±0.5***	2±24	64±36	77±18
RLT1 n=19		11.6±1.4	3.7±0.8	3.5±0.7	2.3±0.7***	2.2±0.6***	6±13	37±11	40±12
RLT2 n=25		15.5±2.3	4.2±1.2	3.7±1.2**	2.9±0.9***	2.6±0.8***	12±18	30±9	38±11

* p<0.05, ** p<0.01, *** p<0.001 more accurate than VO_{2HR}.

DISCUSSION

The results confirmed that On- and Off-dynamics of HR and VO_2 are different during changes in exercise intensity and should be taken into account when estimating VO_2 in field.

The results indicate that $VO_{2HR+ON/OFF}$ and $VO_{2HR+Resp+ON/OFF}$ were able to correct the error in VO_{2HR} estimate due to different VO_2 to HR patterns during On- and Off-responses in bicycle exercise conditions (Figure 2). Accuracy was also significantly enhanced during steady-state bicycle exercise, possibly due to the ability of On- and Off- information to correct different proportions of VO_2 and HR drift (Table 1) and natural changes in power, HR and VO_2 during steady state.

Information on On- and Off- dynamics and respiration rate also differentiated between dynamically changing low-intensity exercise and psycho-physiologically related HR responses, since VO_2 estimation was enhanced during low intensity exercise simulating daily activities (RLT).

Methods presented reduce very significantly the error in VO_2 estimation, and can provide a new level of accuracy for field applications, since On- and Off- dynamics and respiration rate can be estimated reliably from RR-interval data only (e.g. Saalasti, S. 2003, Neural Networks for Heart Rate Time Series Analysis. Academic Dissertation, University of Jyväskylä, Jyväskylä, Finland).

CONCLUSIONS

1. On- and Off- dynamics of VO_2 and HR are different.
2. HR based VO_2 estimation can be enhanced using information on On- and Off- dynamics during: a) dynamically changing exercise intensity, b) steady-state exercise and c) low intensity exercise simulating daily activities.
3. On- and Off-response dynamics and respiration rate can be derived reliably using beat-to-beat RR-interval data only allowing more accurate VO_2 estimation for field applications.

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