VO_2 Estimation Method Based on Heart Rate Measurement

White paper by Firstbeat Technologies Ltd.

This white paper has been produced to review the method and empirical results of the VO2 estimation method developed by Firstbeat Technologies Ltd. Parts of this paper may have been published elsewhere and are referred to in this document.

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INTRODUCTION

This document describes the estimation method for oxygen consumption (VO_2) developed by Firstbeat Technologies Ltd. The estimation is based on measurement of heart rate (HR), beat-by-beat R-R –derived respiration rate and on/off-response information derived from heart beat data.

VO_2 is considered the most accurate variable to evaluate the intensity of aerobic activity. For example, the exercise intensity recommendations of the American College of Sports Medicine (ACSM 2001) are based on using VO_2 as the reference measure.

VO_2 is measured directly in laboratories with metabolic carts or respiratory gas analysers. However, these methods are time consuming, expensive and not applicable for field measurements. HR is often considered the least invasive and most easily measurable parameter related to VO_2, with a well-established relationship to VO_2 especially at high exercise intensities. For this reason, HR is widely used for indirect estimations of VO_2 and the intensity level of exercise.

Literature shows numerous studies modelling the relationship between steady state VO_2 and heart rate. There are, however, several confounding factors influencing the use of heart rate level information in the assessment of VO_2 during training and daily life.

Current HR level –based VO_2 estimation methods:

- are based on steady state conditions only and do not take into account the inconsistency in the HR-VO_2 relationship during dynamically changing exercise intensities
- preferably need laboratory calibration for individual HR to VO_2 equation
- are inaccurate or assume a constant level of VO_2 when HR is low (e.g. the HR-flex method)
- do not distinguish between non-metabolic and metabolic increases in HR (e.g. mental and non-exercise related physical stress)

All this implies that many applications would benefit from better methods of providing an indirect estimate of VO_2. Currently, the best HR level –based VO_2 estimates do not have the sensitivity for tracking detailed changes in VO_2 because the heart rate level is influenced not only by VO_2 but also by other factors.

METHOD FOR VO2 ESTIMATION

To construct a more accurate estimate of VO_2 when compared with previous HR-based estimates, additional information describing bodily functions was added to the model. Neural networks were used to construct a model that derives VO_2 from R-R intervals (time between successive heart beats), using respiration rate and on/off-response information. Schematic illustration of the model is presented in Figure 1. This VO_2 estimation method is implemented in the Firstbeat Technologies Ltd. software.

Respiration rate and VO_2 were found to be strongly correlative (Pulkkinen et al. 2003), and therefore, respiration rate can distinguish metabolic from non-metabolic changes in heart rate. Consequently, respiration rate was added to the model. For more details on the method of deriving the respiration rate from the R-R interval, see Saalasti 2003 and Saalasti et al. 2002.

Differences in the HR-VO_2 relationship during different exercise phases – for example on/off-response, steady state or HR and VO_2 drift during hard exercise (Figure 3, Table 1) – led us to take this information into account in our model to decrease the error of the present linear equations. The measure characterizing the on/off-dynamics is also derived from heart beat data. The gradient of the measure is proportional to the on/off-dynamics, for example positive values during an increase in exercise intensity, negative values during recovery from exercise and a zero level during steady state exercise. Three typical exercise states are presented in Figure 4.

Table 1. HR (bpm) and VO2 (ml/kg/min) drift during bicycle exercises. (Pulkkinen 2003; Pulkkinen et al. 2004)

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***

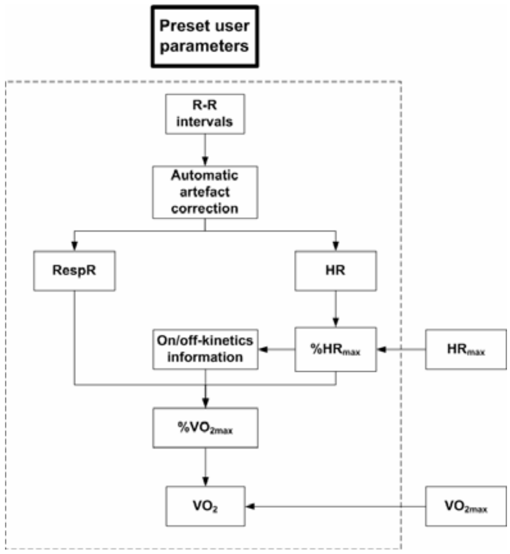

Figure 1. Model of HR-derived VO_2-estimation. $HR_{(max)}$ = (maximal) heart rate, RespR = respiration rate.

MODEL VALIDATION

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. The procedure is presented in Figure 2. Measurements included submaximal steady state and maximal incremental bicycle ergometer (Ergoline, Bitz, Germany) exercises and real-life tasks (RLT). RLTs included simulated low-intensity activities, such as household, recreational and occupational tasks. (See Pulkkinen et al. 2004)

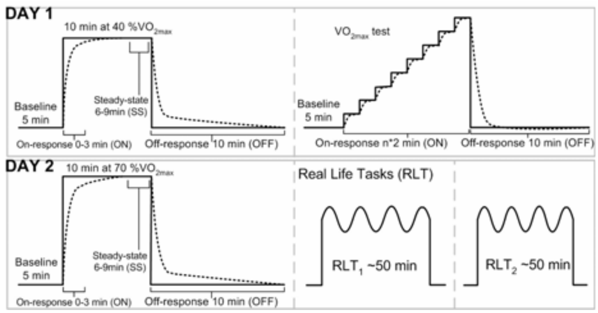

Figure 2. The procedure

HR data was collected with an RR-recorder (Polar Electro Ltd., Kempele, Finland). During bicycle ergometer exercises, VO_2 data was collected breath-by-breath by using a Vmax analyzer (Sensor Medics, California, Palo Alto, USA), and during RLTs, by using a portable Cosmed K4 analyzer (S.r.I, Italy), both of which were calibrated before and after each exercise.

To evaluate, step-by-step, the effects of additional information on the accuracy, four different second-by-second VO_2 estimation models were constructed:

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

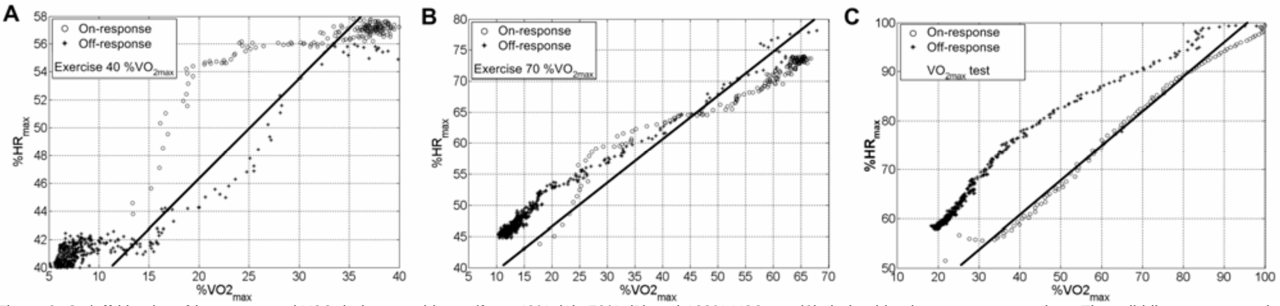

Figure 3. On/off-kinetics of heart rate and VO2 during transition to/from 40% (A), 70% (B) and 100% VO2max (C) during bicycle ergometer exercises. The solid line represents the equation (%VO2max=1.408%HRmax-45.1) by Londeree et al. (1995), who made a linear steady state HR-VO2 model for bicycle ergometer exercise. The equation can be considered to represent many other linear equations, which have been formed with steady state values of HR and VO2 during exercise. (Modified from Pulkkinen 2003; Pulkkinen et al. 2004)

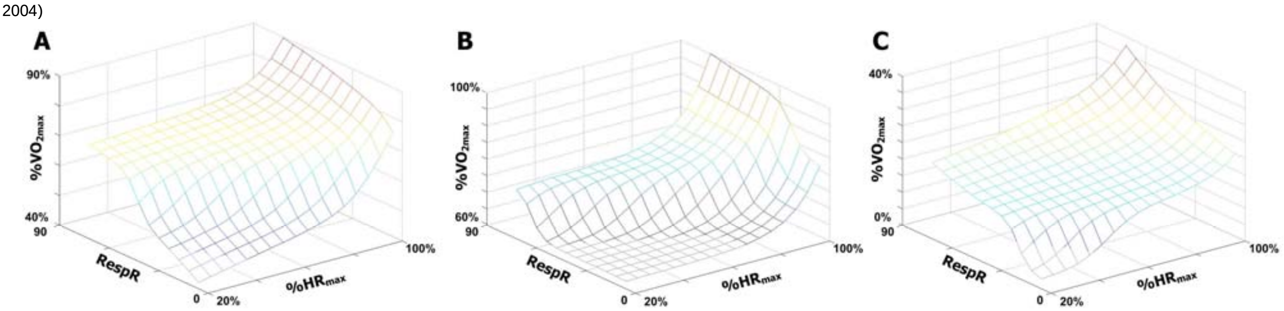

Figure 4. %VO2max as a function of respiration rate and %HRmax during three typical exercise phases: A) steady state, B) on-response and C) off-response. Exercise phases suggested by the index characterizing the on/off-dynamics.

The accuracy of the estimates was evaluated using a whole dataset by mean absolute errors (MAE=mean (| true - estimate |)) and error in percent (%-error) between the measured and estimated values. MAE was calculated second-by-second for each individual time series data to detect even the slightest changes in VO_2 during both on- and off-responses and steady state conditions.

Results

As shown in table 2, adding information to the HR-only estimate (VO_{2HR}) increased the accuracy of the estimation significantly.

Table 2. MAE between measured and estimated VO2, and %-increase in accuracy compared with heart rate only method (VO2HR) including all bicycle and RLT conditions.

	VO_{2HR}	$VO_{2HR+Resp}$	$VO_{2HR+ON/OFF}$	$VO_{2HR+Resp+ON/OFF}$
MAE (ml/kg/min)	3.7	3.3	2.3	1.9
%-increase in accuracy	-	11%	38%	48%

Error was reduced across the whole intensity range (Fig. 5). Greatest increase in accuracy as compared with heart rate only method, 48%, was achieved when using both information on respiration rate and on/off-dynamics.

Note that the error values are calculated on a second-by-second basis, rather than averaging over a longer time period. For more detailed validation information, see Pulkkinen 2003 and Pulkkinen et al. 2003, 2004.

METHOD EVALUATION

In summary, the inclusion of information on respiration rate and on/off-dynamics increased, separately, the accuracy of HR-based VO_2 estimation. The greatest and most consistent improvements were achieved using the model that included information on HR level, respiration rate and on/off-dynamics. All of this information can be derived from R-R interval data, and therefore, this analysis method is also applicable to field measurements.

The developed model was found to be more accurate than the method based only on HR level in several areas:

- At the entire intensity range, from rest to maximal exercise
- During the on-response and during recovery from exercise
- During steady state exercise

The ability of respiration rate to enhance the accuracy of VO_2 estimation is based on the following factors:

- Respiration rate is tightly related to VO_2, providing additional information about true VO_2
- During changes in body positions (e.g. orthostasis), there are only minor changes in VO_2 and respiration rate but major changes in HR
- Respiration rate can distinguish between non-metabolic (e.g. mental and non-exercise related physical stress) and metabolic (physical activity induced) increases in HR.

The ability of the on/off-response information to enhance the accuracy of VO_2 estimation is based on the following factors:

- It corrects the inconsistency in the HR-VO_2 relationship during dynamically changing exercise intensities
- It corrects the overestimation of VO_2 during recovery from exercise when HR tends to remain elevated
- It takes into account and reduces the error caused by proportionally different HR drift and VO_2 slow component during exercise

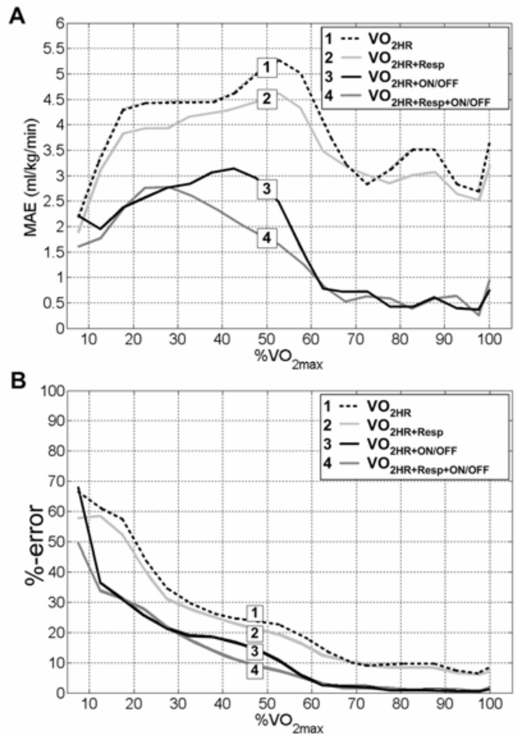

Figure 5. MAE (A) and %-error (B) of VO2 estimation methods across all intensities. MAE=mean (| true - estimate |), %-error = error in percent between the measured and estimated values. (Modified from Pulkkinen 2003; Pulkkinen et al. 2004).

Improvements of accuracy during steady state exercise and rest also appear to be due to the capability of the new calculation model to detect even the smallest VO_2 fluctuations caused by changes in respiration (breath-by-breath) and muscle recruitment patterns, among others.

The described method provides a new, reliable estimation method of VO_2 also at low-intensity exercise, while most previous methods (e.g. the Flex-method) have applied a fixed VO_2 value for all different low-intensity exercises.

PRACTICAL USE

The described VO_2 estimation enables new applications and has several benefits. It is a valid tool for the purposes of research, coaching and personal monitoring, evaluating not only physical activity and training but also the demands of everyday life. The key for using the present VO_2 estimation quickly and easily is simple – through beat-by-beat HR measurement and analysis. The accuracy of the described method is based on true physiological modeling of bodily functions.

Training

The key element in successful exercise prescription and training is accurate information about the intensity of physical activity. As VO_2 is the reference measure for intensity of physical activity prescriptions (ACSM), the present VO_2 estimation method provides an enhancement for training prescription and evaluation of training intensity when compared to methods that are based merely on heart rate levels. For example, it allows a more detailed analysis and comparison of actual and prescribed exercise intensity.

The described VO_2 estimation method can be used to assess the level of aerobic energy production in sports wherein it would be difficult to perform direct VO_2 measurement, for example soccer, basketball, squash, badminton, etc. By estimating the VO_2, the intensity of individual or team training sessions and competitions can be more easily studied and controlled.

Exercise intensity has a central role in conditioning in endurance sports, such as running, cross-country skiing and rowing. Across training periods, inaccuracies in measurement of training intensities may lead to overtraining or suboptimal performance development or peaking.

Ambulatory monitoring during daily life

The presented VO_2 estimation method can be used to detect small and short-term increases in physical activity level during normal daily routines. These include, for example, walking stairs or walking to work, thus recognizing health-promoting activities in real life testing situations.

For research in exercise or health sciences, reliable and non-invasive VO_2 estimation method offers a possibility for ambulatory field measurements and analysis of large populations. This allows a better understanding about the relationship between physical activity and health, for example.

The applicability of the VO_2 estimation to real-life monitoring is based on its capacity to accurately estimate VO_2 also during low-intensity physical activity (in addition to high-intensity activity) by distinguishing between metabolic and non-metabolic responses in HR. Therefore, it is able to track the level of aerobic metabolism at the entire intensity range, from rest to the level of individual VO_{2max}.

Notes and limitations

The VO_2 estimation method presented above has certain limitations when compared to laboratory measurements measuring VO_2 directly. It is important to note that the method is not suitable, as such, for direct estimation of maximal oxygen uptake (VO_{2max}). The accuracy of the method is dependent on the accuracy of personal background parameters, and therefore, measuring the true personal maximal heart rate and maximal oxygen uptake increases the accuracy of the estimation.

The method does not measure anaerobic energy production and can only be utilized to estimate the aerobic proportion of energy production of typical anaerobic exercises, such as sprinting, power lifting, etc.

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For more information:

Firstbeat Technologies Ltd.
Rautpohjankatu 6
FIN-40700 Jyväskylä
Finland

info@firstbeattechnologies.com
www.firstbeattechnologies.com

