INTRODUCTION

This document describes the estimation method for oxygen consumption (VO2) 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.

VO2 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 VO2 as the reference measure.

VO2 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 considered the most invasive and most easily measurable parameter related to VO2, with a well-established relationship to VO2 especially at high exercise intensities. For this reason, HR is widely used for indirect estimations of VO2 and the intensity level of exercise.

Literature shows numerous studies modelling the relationship between steady state VO2 and heart rate. There are, however, several confounding factors influencing the use of heart rate level information in the assessment of VO2 during training and daily life.

Current HR level–based VO2 estimation methods:
- are based on steady state conditions only and do not take into account the inconsistency in the HR–VO2 relationship during dynamically changing exercise intensities
- preferably need laboratory calibration for individual HR to VO2 equation
- are inaccurate or assume a constant level of VO2 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 VO2. Currently, the best HR level–based VO2 estimates do not have the sensitivity for tracking detailed changes in VO2 because the heart rate level is influenced not only by VO2 but also by other factors.

METHOD FOR VO2 ESTIMATION

To construct a more accurate estimate of VO2 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 VO2 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 VO2 estimation method is implemented in the Firstbeat Technologies Ltd. software.

Respiration rate and VO2 were found to be strongly correlated (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–VO2 relationship during different exercise phases – for example on/off-response, steady state or HR and VO2 drift during hard exercise (Figure 4, 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 3.

<table>
<thead>
<tr>
<th>Time</th>
<th>VO2 (ml/kg/min)</th>
<th>VO2 (ml/kg/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3&quot;</td>
<td>17.0±3.7</td>
<td>104±8</td>
</tr>
<tr>
<td>8&quot;</td>
<td>17.6±3.7</td>
<td>106±9</td>
</tr>
</tbody>
</table>

Figure 1. Model of HR-derived VO2-estimation. HR\textsubscript{max} = (maximal) heart rate, Resp\textsubscript{R(max)} = (maximal) 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 VO2\textsubscript{max} 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)

To evaluate, step-by-step, the effects of additional information on the accuracy, four different second-by-second VO2 estimation models were constructed:

1. From HR only (VO2HR)
2. From HR and respiration rate (VO2HR+Resp)
3. From HR and On- and Off- VO2 dynamics (VO2HR+ON/OFF)
4. From HR, respiration rate and On- and Off- VO2 dynamics (VO2HR+Resp+ON/OFF)

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 VO2 during both on- and off-responses and steady state conditions.
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Figure 3. %VO₂max as a function of %RespRmax (x-axis) and %HRmax (y-axis) 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.

Results
As shown in table 2, adding information to the HR-only estimate (VO₂HR) 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.

<table>
<thead>
<tr>
<th></th>
<th>VO₂HR</th>
<th>VO₂HR+Resp</th>
<th>VO₂HR+ON/OFF</th>
<th>VO₂HR+Resp+ON/OFF</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAE (ml/kg/min)</td>
<td>3.7</td>
<td>3.3</td>
<td>2.3</td>
<td>1.9</td>
</tr>
<tr>
<td>% increase in accuracy</td>
<td>-</td>
<td>11%</td>
<td>18%</td>
<td>48%</td>
</tr>
</tbody>
</table>

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 VO₂ 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 VO₂ estimation is based on the following factors:

- Respiration rate is tightly related to VO₂, providing additional information about true VO₂
- During changes in body positions (e.g. orthostasis), there are only minor changes in VO₂ 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 VO₂ estimation is based on the following factors:

- It corrects the inconsistency in the HR-VO₂ relationship during dynamically changing exercise intensities
- It corrects the overestimation of VO₂ 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 VO₂ 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).
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PRACTICAL USE

The described VO₂ estimation method provides 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 VO₂ estimation quickly and easily is simplicity – through heat-by-heart 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 VO₂ is the reference measure for intensity of physical activity prescriptions (ACSM), the present VO₂ 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 VO₂ estimation method can be used to assess the level of aerobic energy production in sports wherein it would be difficult to perform direct VO₂ measurement, for example soccer, basketball, squash, badminton, etc. By estimating the VO₂, 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 VO₂ 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 VO₂ 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 VO₂ estimation to real-life monitoring is based on its capacity to accurately estimate VO₂ 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 VO₂max.

Notes and limitations

The VO₂ estimation method presented above has certain limitations when compared to laboratory measurements measuring VO₂ directly. It is important to note that the method is not suitable, as such, for direct estimation of maximal oxygen uptake (VO₂max). The accuracy of the method is dependent on the accuracy of personal background parameters, and therefore, measuring the true personal maximal heart rate, maximal oxygen uptake and maximal respiration rate 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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