Indirect EPOC Prediction 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 an indirect EPOC measurement method developed by Firstbeat Technologies Ltd. Parts of this paper may have been published elsewhere and are referred to in this document.

INTRODUCTION
This document describes a method for EPOC (excess post-exercise oxygen consumption) prediction based on heart rate (HR) measurement. EPOC is defined as the excess oxygen consumed during recovery from exercise as compared to resting oxygen consumption. The EPOC prediction method has been developed to provide a physiology-based measure for training load assessment.

Training load assessment
It is difficult to select an optimal exercise dose. Sufficiently strenuous exercise causes a disturbance in body’s homeostasis which after recovery results in improved fitness (e.g. Brooks & Fahey 1984; Astrand & Rodahl 1986). Too easy training does not improve fitness but too hard training may in long term lead to overtraining. It is therefore important to measure the training load.

Methods that are used in assessing training load may be broadly characterized as subjective and physiological measures. Subjective measures are easy to access, but do not always reflect physiological responses and recovery demand. Traditional physiological measures, such as VO2, heart rate and blood lactate, reflect mainly momentary intensity of exercise and not length of exercise or cumulative exercise load. There are also training load measures such as training impulse (TRIMP), but which does not have physiological basis or scale and therefore may be difficult to interpret.

EPOC is a physiological measure (amount of oxygen consumed in excess after exercise as measured in liters or ml/kg) that reflects the recovery demand and the disturbance of body’s homeostasis brought by the exercise. Measurement of EPOC has been possible only by analyzing respiratory gases with laboratory equipment, thus being expensive, time consuming and not applicable to everyday purposes.

The lack of valid and easy-to-apply physiology based method for the assessment of training load has led us to develop a method to estimate EPOC indirectly from heart rate measurement.

EPOC in exercise sciences
The first observation of an elevated resting metabolic rate after exercise was made in 1910 by Benedict and Carpenter and was later studied as “oxygen debt” (Hill and Lupton in 1923). The present name EPOC has been used not only to represent oxygen repayment during recovery but also to reflect the general exercise-induced disturbance of body’s resting metabolism (Gaesser & Brooks 1984; Gore & Withers 1990) and resting homeostasis (Brehm & Gutin 1986): “the cause of Excessive Post-Exercise Oxygen Consumption (EPOC) is the general disturbance to homeostasis brought on by exercise” (Brooks & Fahey 1984).

EPOC reflects the body’s recovery requirements after exercise. Active oxygen-consuming recovery processes occurring in the body are due to replenishment of body’s resources (O2-stores, ATP, CP) and increased metabolic rate (increased HR and respiratory work, elevated body temperature) caused by metabolic by-products and hormones produced during exercise. (Brooks & Fahey 1984; Astrand & Rodahl 1986; Børsheim & Bahr 2003)

- EPOC reflects a general disturbance in body’s homeostasis caused by exercise.
- EPOC is calculated by subtracting the area under resting VO2 from the area under the recovery VO2 curve (see Figures 1 and 4).
- EPOC gets higher with higher intensity and/or longer duration of exercise (e.g. Børsheim & Bahr 2003) (see Figures 3 and 4).

CONSTRUCTION OF THE MODEL FOR HEART RATE BASED EPOC PREDICTION
The EPOC model was constructed based on meta-analysis data of peer-reviewed articles. Only valid studies were carefully selected for this purpose. The data included 48 different exercise settings, including a total of 158 trained and untrained male and female subjects. Exercise durations ranged from 2 to 180 minutes and exercise intensities from 18 to 108% of VO2max. The modeling data included both continuous and intermittent exercises and consisted of running, cycling and upper-body ergometer exercise.

EPOC is predicted only on the basis of heart rate derived information (see Figure 2). The variables used in the estimation are current intensity (%VO2max) and duration of exercise (time between two sampling points, Δt) and EPOC in the previous sampling point. The model is able to predict the amount of EPOC at any given moment. No post-exercise measurement is needed (see Figure 1). The model can be mathematically described as follows:

$$EPOC_{pred} = f(\text{current intensity}, \text{exercise duration}, \text{EPOC in previous sample})$$

At low exercise intensity (<30-40%VO2max), EPOC does not accumulate significantly after the initial increase at the beginning of exercise (see Figure 3). At higher exercise intensities (>50%VO2max), EPOC accumulates continuously. The slope of accumulation gets steeper with increasing intensity.
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Figure 4. EPOC_{meas} (shaded area) and EPOC_{pred} (dotted line) from four sample exercises. Figures A to C represent typical constant-intensity exercises, whereas Figure D represents a typical exercise during which the intensity changes naturally, for example according to speed (e.g. running, cycling, skating or rowing), work rate (e.g. indoor rowing or cycle ergometry) or terrain (uphill/downhill).

Figure 5. Calculation models of the EPOC_{pred} upslope component (A) and downslope component (B), fitted using meta-analysis data. The combination of upslope and downslope equations determines the gradient of EPOC_{pred} accumulation.

The accumulation formula of HR-based EPOC is a combination of upslope (Fig. 4 A) and downslope (Fig. 4 B) formulas. When the intensity of exercise is high, EPOC accumulates, whereas during periods of rest or low-intensity activity, the combination of these formulas results in decreasing EPOC.

There may be a time lag of about 15 s between the cessation of exercise and reaching the peak value of heart beat derived EPOC. This is due to the slow recovery pattern of VO2 after exercise, which lags behind the true intensity (the calculation model is not able to recognize the exact end point of exercise).

MODEL VALIDATION (Data published, Rusko et al. 2003)

Methods
Subjects were 32 healthy adults (8 fit and 8 less fit males and females), age 38±9 years (mean±SD), weight 69.6±10.8 kg, height 171.6±8.5 cm and VO2_max 44.0±8.8 ml/kg/min. The procedure is presented in Figure 6. Measurements included two 10-min submaximal steady state exercise sessions at 40% and 70% VO2_max, with a constant load, and a maximal incremental bicycle ergometer (Ergoline, Bitz, Germany) test to voluntary exhaustion. Heart period data was collected beat-by-beat with an RR-recorder (Polar Electro Ltd., Kempele, Finland) and VO2 data breath-by-breath with a Vmax-analyzer (Sensor Medics, California, Palo Alto, USA).

Results
HR-based EPOC was found to correlate with measured EPOC and the goodness of fit (r^2) value was 0.79 (see Figure 7). Mean absolute error (MAE) values for the HR-based EPOC, when compared to the measured EPOC values, were 9.4, 14.0 and 16.9 ml/kg for 40% and 70% constant load exercise and for maximal incremental exercise, respectively. For the pooled data, MAE was 13.7 ml/kg. HR-based EPOC was also tightly connected with blood lactate levels, with the r^2 value being 0.79 (see Figure 8).
Table 1 summarizes the properties of exercise that determine the magnitude of EPOC. During exercise, EPOC increases or decreases depending on whether disturbance or recovery in homeostasis is expected. EPOC starts to decrease if the intensity decreases enough during exercise. This implies that the physiological training load is not increasing further, but is decreasing instead.

High EPOC-values are typically attained in exercise where cardiorespiratory load and oxygen consumption remain at high level without possibility to recover. Exercise that recruits large muscle mass, such as cross-country skiing and running, results in higher EPOC values than exercise that recruits small muscle mass. High EPOC values are also gained in intermittent exercise, such as interval training, soccer or squash, if recovery periods are short and intensity remains moderate. When applied to same exercise type, EPOC can be used to compare the demand of different exercises.

EPOC reflects mainly aerobic properties of the exercise and therefore, does not reflect optimally exhaustion due to local muscular fatigue and/or acidity. Thus, in strength exercise, EPOC may be low although the individual would be exhausted.

The day-to-day variation in the physiological training state of an individual can be tracked with EPOC. Short-term changes in performance, environmental factors and possible illnesses affect EPOC accumulation. EPOC is a sensitive measure for both cardiac and respiratory responses. Even slightly unusual responses can be tracked (see Table 2).

Table 1. EPOC depends on exercise properties.

<table>
<thead>
<tr>
<th>Higher EPOC</th>
<th>Lower EPOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increased intensity</td>
<td>Decreased intensity</td>
</tr>
<tr>
<td>Longer duration</td>
<td>Shorter duration</td>
</tr>
<tr>
<td>Continuous exercise</td>
<td>Discontinuous exercise</td>
</tr>
<tr>
<td>Shorter recovery periods during intermittent exercise</td>
<td>Longer recovery periods during intermittent exercise</td>
</tr>
<tr>
<td>Active recovery during intermittent exercise</td>
<td>Passive recovery during intermittent exercise</td>
</tr>
<tr>
<td>Whole body exercise</td>
<td>Lower/upper body exercise</td>
</tr>
</tbody>
</table>

Table 2. Factors causing higher or lower HR-based EPOC values when compared to usual values.

<table>
<thead>
<tr>
<th>Possible cause</th>
<th>Recommended action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decreased fitness level.</td>
<td>Continue training. If possible, reduce the EPOC level back to normal or slightly below it.</td>
</tr>
<tr>
<td>Environmental conditions: increased altitude, temperature or humidity.</td>
<td>Decrease absolute work rate to match previous EPOC levels.</td>
</tr>
<tr>
<td>Not fully recovered from previous exercise.</td>
<td>Decrease training load and maximize recovery.</td>
</tr>
<tr>
<td>Illness.</td>
<td>Do not exercise if you suffer from an illness.</td>
</tr>
</tbody>
</table>

Applications of EPOC in Training

Controlling the training load during a single exercise session

EPOC can be applied across sports, as can be seen from Table 4. An individual willing to improve his/her fitness level can try different sports and check which ones are the best for his/her purpose.

EPOC can be used to confirm whether exercise fulfilled the purpose set before the exercise session. Table 3 represents the main types of aerobic exercise and the expected EPOC response. If the purpose is to enhance maximal aerobic fitness, EPOC should be high (see Figures 9 A and B). During low-intensity basic endurance exercise and separate warm-up exercises, EPOC should be kept at a low level. During cool-down, a decline in EPOC should be seen, indicating active recovery after exercise.

EPOC is useful in monitoring day-to-day changes in the physiological response to training. If there is an unexpected EPOC response, the training program can be adjusted depending on the cause of the different response. See Table 2 for additional explanations for higher or lower EPOC values than usual. More fit individuals are able to exercise at the same relative intensity for a longer period of time than less fit individuals, which leads to higher EPOC.

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When coaching a team, it is important to get information on the physiological responses of each individual. Team training sessions and games have a different impact on each player due to individual differences in e.g. fitness level, position, game style and motivation. With EPOC, the training load of each individual player can be monitored and the training program adjusted (e.g. some players may need more intense training while others need more rest after the games). See Figures 9 C and 9 D for an example in soccer.

Programming and periodization of training
The overall load that accumulates during training periods can also be evaluated with EPOC. A schematic example of training load over a training period of an endurance athlete is presented in Figure 10. The integration of training intensity and duration enables easier quantitative analysis of training. More accurate analysis of previous training loads helps in determining recovery requirements and designing subsequent training sessions optimally: the training load can be increased if the previous load is considered to have been too low, or decreased if the load had been higher than planned.

Figure 9. Examples of the accumulation of HR-based EPOC in different exercise sessions: (A) High-intensity interval training session (Nordic walking/running in a steep uphill). (B) High-intensity constant velocity running exercise. (C) A soccer player (defense) from the Finnish national league during a pre-season practice match. (D) A player from the same team (mid-fielder) in the same match. Note the difference in physiological load between the two players. The match was preceded by a 20-min warm-up and there was a half-time of about 10 min between the two halves.

Figure 10. A schematic representation of an endurance athlete’s training load during eight successive weeks (the columns represent daily values of EPOC). This two-month period prepares the athlete for the most important races of the season. The daily values are highest during weekends mainly due to races. Note also the less loading days before race days.
Table 4. Accumulation of HR-based EPOC values in different sports.

<table>
<thead>
<tr>
<th>Sport/activity</th>
<th>Typical exercise</th>
<th>Impact on maximal aerobic fitness (VO2max)</th>
<th>Typical EPOC (ml/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Running</td>
<td>10-km race (27-50 min, 70-90%VO2max)</td>
<td>High – Very high</td>
<td>120-260</td>
</tr>
<tr>
<td></td>
<td>Marathon 42 km (2h 10min - 5h, 65-85%VO2max)</td>
<td>High – Very high</td>
<td>120-650</td>
</tr>
<tr>
<td></td>
<td>60 min low intensity (55-65%VO2max)</td>
<td>Low – Moderate</td>
<td>40-90</td>
</tr>
<tr>
<td>Walking</td>
<td>Brisk walk 1h (40-50%VO2max)</td>
<td>Low</td>
<td>10-25</td>
</tr>
<tr>
<td></td>
<td>Trekking with a backpack in hilly terrain for 5h (50-60%VO2max)</td>
<td>Low – Moderate</td>
<td>25-75</td>
</tr>
<tr>
<td>Cycling</td>
<td>Spinning session 40 min (60-80%VO2max)</td>
<td>Moderate – Very high</td>
<td>50-200</td>
</tr>
<tr>
<td></td>
<td>Cycling to work 20 min (50-50%VO2max)</td>
<td>Low</td>
<td>5-15</td>
</tr>
<tr>
<td>Rowing</td>
<td>Aerobic workout with ergometer 30 min (60-75%VO2max)</td>
<td>Moderate – High</td>
<td>60-120</td>
</tr>
<tr>
<td></td>
<td>Warm-up at gym with ergometer 10 min (55-65%VO2max)</td>
<td>Low</td>
<td>15-25</td>
</tr>
<tr>
<td>Cross-Country Skiing</td>
<td>15-km race (35-60min, 70-85%VO2max)</td>
<td>High – Very high</td>
<td>130-320</td>
</tr>
<tr>
<td></td>
<td>90-km race (e.g. Vasaloppet: 3h 40 min-10 h, 50-80% VO2max)</td>
<td>Low – Very high</td>
<td>30-550</td>
</tr>
<tr>
<td>Soccer</td>
<td>Game 90 min, position: back</td>
<td>Low – High</td>
<td>30-150</td>
</tr>
<tr>
<td></td>
<td>Game 90 min, position: midfielder, offence</td>
<td>High – Very high</td>
<td>150-300</td>
</tr>
<tr>
<td>Aerobics</td>
<td>45 min aerobics class (60-85%VO2max)</td>
<td>Moderate – Very high</td>
<td>70-200</td>
</tr>
<tr>
<td>Badminton, Squash</td>
<td>1h game (70-80%VO2max)</td>
<td>High – Very high</td>
<td>130-280</td>
</tr>
<tr>
<td>Tennis</td>
<td>1h game (50-70%VO2max)</td>
<td>Low – High</td>
<td>25-130</td>
</tr>
<tr>
<td>Golf</td>
<td>Playing 18 holes (about 3 hours, 30-40%VO2max)</td>
<td>Very low – Low</td>
<td>5-10</td>
</tr>
</tbody>
</table>

**REFERENCES AND FURTHER READING**


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