

An Energy Expenditure Estimation Method Based on Heart Rate Measurement

Firstbeat Technologies Ltd.

This white paper has been produced to review the method and empirical results related to the heart beat based estimation of energy expenditure 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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THE HEART RATE BASED ENERGY EXPENDITURE ESTIMATION METHOD AT GLANCE

- The described energy expenditure (EE) estimation method is based on a well-known relationship between cardiorespiratory function and measured energy expenditure.
- The accuracy of the described heart beat based EE-estimation method is substantially better than the accuracy of traditional heart rate level based estimation.
- Increased accuracy is due to methods ability to utilize information on respiration rate and on/off-kinetics of oxygen consumption, as well as information on body's metabolism.
- The method is easy to use. No individual calibration of heart rate levels is needed and only heart beat data and personal background parameters (e.g. age, height, weight, gender and physical activity level) are required for the estimation.
- The method can be used in all conditions, from rest to maximal exercise, and also allows detailed measurements during dynamically changing exercise and resting conditions.
- As a non-invasive measurement tool, Firstbeat EE-estimation can be applied to both personal and professional purposes, including weight management, promotion of physical activity and lifestyle assessments, and fitness training.
- The method can be also used for research purposes to extend EE measurement from laboratory to the field.

INTRODUCTION

This document presents a method for heart beat (R-R) based estimation of energy expenditure. This methods applies a wide range of heart beat derived physiological functions that provides increased accuracy and is yet very simple to use.

The level of daily physical activity has a great effect on a person's health. During the last decades, sedentary and inactive lifestyles have caused serious health-related concerns. The assessment of energy expenditure in real life has become increasingly important, since it may help to identify inactive lifestyles and to motivate towards more active lifestyle. Energy expenditure is often assessed along with energy intake for weight management purposes. Whereas the assessment of energy expenditure can play a role in promoting a healthy lifestyle, energy expenditure measurements are also important in the study of relationships between physical activity and health.

In addition to health promotion and health-related research, energy expenditure measurements can also be utilized in fitness and athletic training. Athletes and

active sports participants, together with their coaches and personal trainers, can plan their nutrition by utilizing information on expended calories.

The measurement of EE is possible with different methods, including direct and indirect calorimetry, the doubly labeled water technique, activity diaries and questionnaires, as well as methods that utilize information on heart rate or motion. All methods have their advantages and limitations, and generally the selection of most optimal method depends on purpose of use.

Heart rate (HR) is probably the most frequently used indirect parameter in EE-assessment, mainly due to following reasons:

- HR is easy to measure.
- EE is easily accessible from HR data.
- HR-based EE-estimates are relatively accurate in steady exercise conditions.

Despite these advantages, conventional HR level-based energy expenditure estimation methods have also the following limitations:

- Assumption of steady state conditions does not take into account the inconsistencies in the HR-EE relationship (for example, when exercise intensity changes dynamically)
- To gain best accuracy, HR-level based methods need individual laboratory calibration for relating HR to EE.
- Traditional methods are inaccurate or assume a constant level of EE at low intensity of physical activity
- Non-metabolic increases in HR influence the results (e.g. mental and non-exercise related physical stress).
- Changes in body's metabolism that occur during prolonged physical activity or recovery are not taken into account.

Firstbeat Technologies has developed a novel EE estimation method that is also based on heart rate information. This method is based on analysis of beat-by-beat heart rate data. The aim of this method has been to resolve the problems that cause errors in traditional EE-estimates.

ENERGY EXPENDITURE ESTIMATION METHOD

The estimation of total energy expenditure advances in two stages: At first, oxygen consumption (VO₂) is estimated. EE is further derived based on information on VO₂ and estimated metabolic events in the body. The described energy expenditure estimation model has been constructed using neural network modeling. Figure 1 shows an overall view of the EE estimation model.

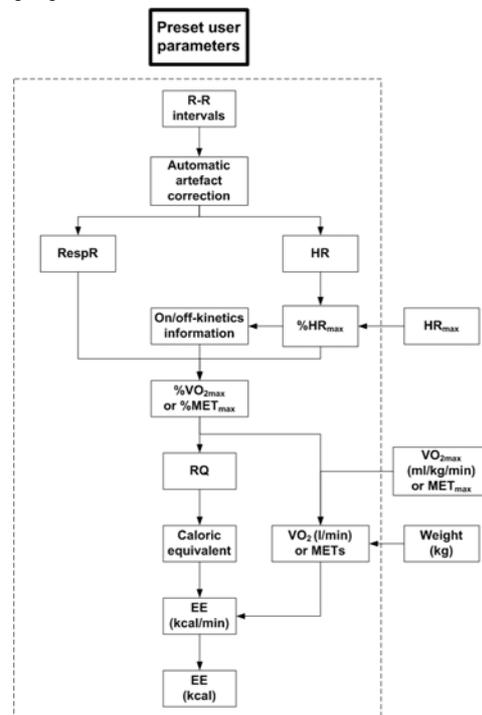


Figure 1. Model for deriving energy expenditure (EE) from heart beat data. RespR = respiration rate, HR(max) = (maximal) heart rate, VO₂(max) = (maximal) oxygen consumption, MET(max) = (maximal) metabolic equivalent: VO₂ during physical activity proportioned to resting VO₂, RQ = respiratory quotient.

VO₂ estimation

The energy expenditure estimation method described in this document is based on the VO₂ estimation method that is described in detail in the VO₂ White Paper. Shortly, in addition to utilizing HR information, the described VO₂ estimation method also utilizes information on respiration rate and on/off-kinetics of VO₂ derived from R-R-intervals (time interval between two consecutive heart beats).

METs (Metabolic Equivalent), multiples of resting metabolic rate are commonly used to represent intensity of physical exercise. VO₂ -values can be converted to METs by dividing VO₂ with a constant value of 3.5. One MET is therefore equal to a VO₂ of 3.5 ml/kg/min which is the amount of oxygen the body uses at rest. METs can be used in the described calculation model instead of VO₂.

Personal maximal heart rate (HR_{max}) and maximal oxygen consumption (VO_{2max}) or maximal METs (MET_{max}) are used in the calculation of momentary VO₂. HR_{max} and VO_{2max} (MET_{max}) can be estimated on the basis of personal background parameters, if the values have not been measured (Jackson et al. 1990; Jones 1988).

Energy expenditure is calculated by using information on metabolic events occurring in the body

In the described calculation model, energy expenditure is calculated on the basis of information on VO₂ (or METs), respiratory quotient (RQ) and caloric equivalent. RQ describes the ratio between carbon dioxide produced and oxygen consumed in metabolism, varying from 0.70 to 1.00. RQ has a well-established deterministic relationship with caloric equivalent (=thermal equivalent), which describes the amount of energy expended per one liter of consumed oxygen, varying from 4.69 to 5.05 kcal/l O₂ (for the relationships between substrate use, RQ and caloric equivalent, see e.g. McArdle et al. 1996).

Both exercise intensity and duration affect RQ and caloric equivalent, which is a well-known phenomenon established in literature. An increase in exercise intensity results in increased RQ and caloric equivalent due to the increased oxidation of carbohydrate and decreased oxidation of fat. Prolonged exercise duration, on the other hand, has an opposite effect due to the increased oxidation of fat and decreased oxidation of carbohydrate.

When momentary VO₂ (or METs) and caloric equivalent are known, it is possible to calculate momentary energy expenditure. Total energy expenditure can be calculated by summing up the momentary EE-values.

The described EE-estimation estimates only the aerobic component of energy expenditure, which may cause slight underestimation of EE during short-term anaerobic activities lasting from few seconds to a couple of minutes. However, the underestimation is insignificant in measurements lasting longer than 2-3 minutes.

MODEL VALIDATION

Data collection

The subjects were 32 healthy adults (16 men, 16 women), 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. 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 (see Figure 2).

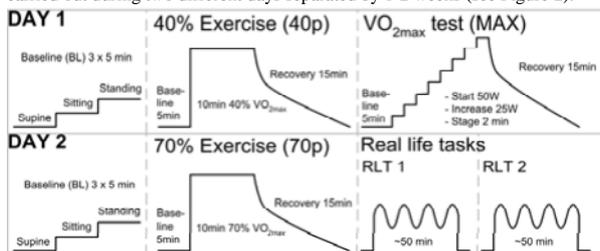


Figure 2. The procedure.

HR data was collected with RR-recorders (Polar Electro Oy, Kempele, Finland). During bicycle ergometer exercises, VO₂ (METs) -data was collected breath-by-breath using a Vmax (Sensor Medics, California, Palo Alto, USA) respiratory gas analyzer, and during RLT's using a portable Cosmed K4 analyzer (S.r.l, Italy), both of which were calibrated before and after each exercise.

The accuracy of the estimates was evaluated with mean absolute error (MAE = mean (| true measured value - estimated value |)) and mean absolute percentage error (MAPE = MAE / true measured value × 100) between the measured and estimated values in the whole dataset. Pearson correlation coefficients were also calculated to assess the accuracy of different EE estimates.

Validation setup 1

A randomly selected data sample representing three percent of the total dataset was used to construct two different neural network (NN) models to estimate second-by-second VO₂ (METs). Energy expenditure was further calculated from the NN-modeled VO₂ (METs):

- Using information on HR-level only (EE_{HR}) and
- Using information on HR, respiration rate and on/off- VO₂ dynamics (EE_{HR+RespR+ON/OFF}).

where both methods utilized information on RQ.

Results

EE_{HR+Resp+ON/OFF} was found to be the most accurate method for EE-estimation in neural network modeling (see Figure 3.) When compared to HR-level only method, the accuracy was enhanced by nearly 50 %.

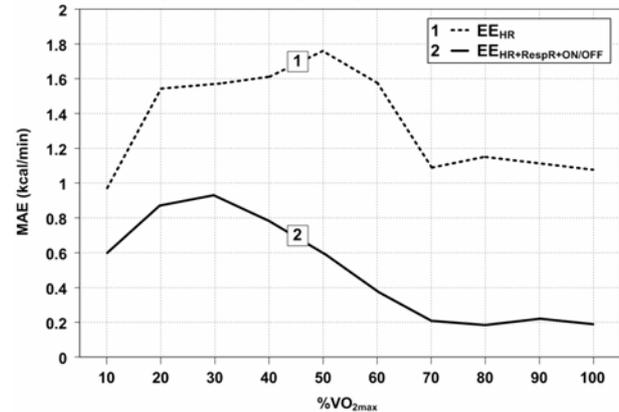


Figure 3. MAE of neural network based EE-estimation methods across all intensities.

Validation setup 2 (See Pulkkinen et al. 2005)

The best neural network model of validation setup 1 – EE_{HR+Resp+ON/OFF} – was later compared with conventional heart rate based EE-estimation models described in the literature. The selected methods included two regression methods earlier used by Rennie et al. (2001) (EE_{RENN}) and Hiilloskorpi et al. (2003) (EE_{HILL}) and two flex-HR methods with both individual (FLEX_{IND}) and general (FLEX_{GEN}) fits for the relationship between HR and EE.

Results

The best neural network model (EE_{HR+Resp+ON/OFF}) had the smallest MAE and MAPE, and highest correlation values when compared with the regression models (Rennie et al. 2001; Hiilloskorpi et al. 2003) and HR-flex methods. By using the neural network model, the accuracy was enhanced by 22 to 60 % when compared to the conventional methods. To see MAE and MAPE values in more detail, see Table 1.

Table 1. Error values of different EE-estimation methods. MAE = Mean absolute error, MAPE = Mean absolute percentage error. The measured mean energy expenditure of the validation measurements was 740 kcal.

Method	MAE (kcal)	MAPE
EE _{HR+Resp+ON/OFF}	73	10.9 %
FLEX _{IND} *	93	13.5 %
FLEX _{GEN}	101	14.4 %
EE _{RENN}	181	22.0 %
EE _{HILL}	180	27.6 %

*Includes personal laboratory calibration

Summary of the validation studies

By including information on respiration rate and on/off-kinetics with HR data, the accuracy of EE-estimation improved significantly. Later, when compared with other conventional types of HR-based EE-estimation methods, EE_{HR+Resp+ON/OFF} was shown to be the most accurate method to estimate EE. The accuracy of EE_{HR+Resp+ON/OFF} was even better than methods with laboratory calibration. Other studies have also produced similar results and have indicated as low as 7 % error for the beat-by-beat method developed by Firstbeat Technologies (Wünsch et al. 2005).

EVALUATION OF THE STRENGTHS AND WEAKNESSES OF DIFFERENT METHODS

At present, several methods are available for the measurement (or estimation) of energy expenditure and all of the methods have some limitations as well as strengths. In all cases it is important to select most appropriate method that suits the purpose in terms of available resources, time, and required accuracy. Table 2 summarizes advantages and limitations of different methods for measuring energy expenditure.

Table 2. An evaluation of the advantages and limitations of different methods to measure energy expenditure. (See also short descriptions of each method in the text.)

Method	Advantages	Limitations
Direct calorimetry	The most accurate method to estimate EE. Minimal error.	Very expensive. Not applicable to measurement in free-living conditions.
Indirect calorimetry	Accurate (error $\approx 5\%$) in the measurement of EE. Breath-by-breath analysis also possible. Portable devices with comparable accuracy are also available.	Expensive. Long-lasting measurements are not possible. Does not allow daily use.
Doubly labeled water	Accurate (error usually smaller than 5%). Well suited for long-term measurements (4-20 days) of a large number of subjects.	Very expensive. No information on short bouts of activity during the measurement period. Only information on the total energy expended.
Firstbeat beat-by-beat based heart rate method	Inexpensive and easy to use. Relatively high accuracy, (error 7-10%), although does not require laboratory calibration. Provides second-by-second estimation of EE.	Larger error than in calorimetry or DLW-techniques. Requires beat-by-beat HR data collection with sufficient accuracy.
Conventional HR-level based estimation using individual laboratory calibration	Relatively inexpensive. Smaller error (15-25%) as compared with general equations (see below). Does not require beat-by-beat data, only heart rate averages need to be stored.	Measurement of large number of subjects is hard due to the complex calibration procedure. Heart rate is affected by factors other than physical activity.
Conventional HR-level based estimation with general equations.	Inexpensive and easy. Does not require beat-by-beat data.	Large potential error (20-35%) in the HR-EE relationship, especially since the individual calibration is not done.
Motion detection based estimation	Inexpensive (or very inexpensive) and usually very easy to measure. Provides reliably summary information on periods of physical activity (e.g. active time).	Large estimation error (20-35%). Uniaxial sensors are not sufficiently sensitive to quantify EE (error up to 60%). Is best suited for identifying periods (time and duration) of physical activity.
Activity diary and questionnaires.	Very inexpensive. Does not necessarily require hardware. Users may benefit from self-evaluation.	Large estimation error (20-60%). No information on instantaneous values of EE. Accurate measurement requires lots of time and learning from the person whose EE is estimated.

Reference-level (laboratory) methods in energy expenditure measurement

Direct calorimetry, indirect calorimetry and the doubly labeled water (DLW) technique are considered as the most accurate methods to measure the level of metabolism, and most other methods are validated against them.

- Direct calorimetry is based on the measurement of human heat production and it measures all the energy expended through either aerobic or anaerobic pathways.
- Indirect calorimetry is based on the measurement of respiratory gases. The method accurately reflects the events that occur in aerobic metabolism, but does not reflect anaerobic metabolism.
- The doubly labeled water technique is based on measuring the metabolism of doubly ($^2\text{H}_2^{18}\text{O}$) labelled water in the body. The method is rather frequently used method in long-lasting free-living measurements.

Energy expenditure estimation methods

Activity diaries and collection of HR and motion data are the most frequently used tools in the field measurement of energy expenditure, due to the easiness of data collection and low cost. However, these methods have differential levels of accuracy when compared to reference (laboratory) methods.

- Activity diaries and questionnaires are used to gather information on a person's physical activity and rely on user's self-reporting.
- Energy expenditure can also be estimated on the basis of motion detection. Motion detection methods include measurement of acceleration (accelerometry) and counting steps (pedometry). Information on body position can be combined with motion data to increase accuracy. Movement is not directly related to metabolism, since movement type and conditions influence the estimation, and movement based methods can not generally describe reliably the intensity of physical activity.
- Traditional heart rate level based methods rely on a general relationship between heart rate and energy expenditure. More accuracy can be obtained by individual laboratory calibration.
- The beat-by-beat HR analysis developed by Firstbeat provides a more sophisticated estimation model for energy expenditure. This model includes additional heart beat derived physiological parameters, providing better accuracy when compared with traditional HR-based EE-estimates. Whereas traditional HR-level only methods usually fail to estimate EE at low and changing HR levels, the described method provides continuous and relatively accurate information on metabolism in all conditions.

THE NEED FOR ACCURATE ENERGY EXPENDITURE ESTIMATION

Most methods produce repeatable results when applied to the same person within the same type of conditions. However, when conditions (e.g., type of physical activity) and individuals change, methods may produce very different results. Accordingly, there are several fields of applications wherein it is important to consider also the validity of the method.

In research, the need for valid methods is obvious, since the use of inaccurate methods may not only violate the study design itself, but may also give groundless information to the research community.

Accurate energy expenditure measures are also important in weight management applications. Whether one is comparing energy expenditure values of different personal physical performances or comparing the daily expenditure with the daily intake, measurement accuracy greatly influences behavioral interpretation and planning of future actions.

The accuracy of daily estimation must be enough to be able to verify required small (e.g. 500 kcal daily energy deficit for monthly weight loss of 2 kilos) difference between daily energy intake and energy expenditure. High sensitivity of measurement is also important, since it helps to recognize short bouts of physical activity during a day, which can be then shown as changes in daily energy expenditure. Accurate information helps individuals to motivate, as even smaller changes can be seen from the measurement.

Some expert organisations such as ACSM (2001) have also recommended that accurate method is needed to verify whether weekly exercise is enough to produce a health promoting effect. One may not be able to make correct conclusions of health effects with a device that is insensitive and biased to estimate energy expenditure caused by different physical activity levels.

PRACTICAL USE OF THE BEAT-BY-BEAT ENERGY EXPENDITURE ESTIMATION

The described EE-estimation that is based on beat-by-beat measurement of heart can be used in different applied settings and purposes. In particular, the presented method enables relatively accurate estimation of 24h energy expenditure.

- More efficient weight management with information on daily energy balance
- Comparison of 24 h energy expenditures profiles between different days
- Setting daily target calories for light physical activity or fitness training
- Observation of actual behavior
- Motivation to more active lifestyle
- Long term weight change prediction based on daily measurements
- Confirming health effects of daily physical activity
- Selection of physical activities that are effective in burning calories
- Athletic nutrition planning
- Extending the use of less sensitive screening methods to more detailed energy expenditure assessments.

Weight management and health monitoring

Daily energy expenditure can be evaluated in detail with the heart beat based method, for example in connection with weight management programs. This method is especially suitable for programs that have an emphasis on weight loss by increased physical activity. Information on the amount of calories consumed is essential in planning an optimal diet. In addition, exercise may be prescribed to support a weight management program. Due to the easy measurement and yet accurate analysis, the described method can be used to understand and communicate one's energy expenditure, thus supporting long-term weight management.

Energy expenditure and activity levels can be also evaluated within lifestyle health evaluation or interventions aimed at changing health behaviour. Health care professionals can have access to observing full-day activity profiles during everyday life. This may help in recognizing the positive and negative aspects of customers daily life and to prescribe an optimal amount of exercise to gain necessary health effects. Personal feedback may help to increase positive and decrease negative behavior models. Figure 4 represents two different daily (24h) EE profiles.

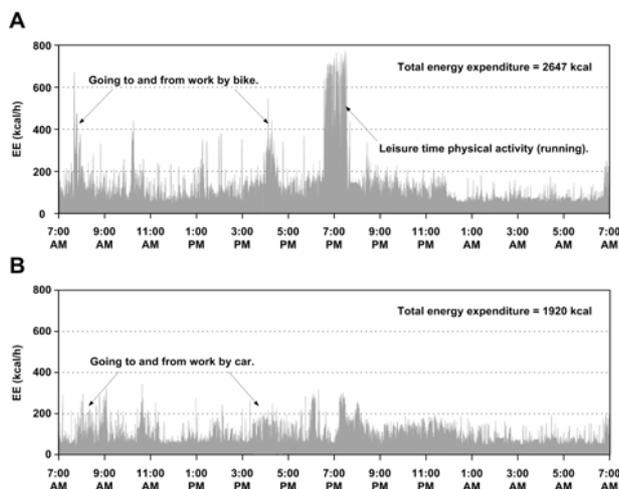


Figure 4. A. An energy expenditure profile during an ordinary day at the office, including cycling to and from work and leisure time physical activity in the evening. B. A similar day at work, but now going to and from work by car. No physical activity in the evening. See the difference in total energy expenditure.

Fitness and sports

Energy expenditure assessments can be also used to support athletic and fitness training. During fitness training it is often typical to compare energy expenditure values between different exercises, and to select the activities that are perceived most positive and also have relatively high energy expenditure.

Coach and athlete can design athlete's daily diet by considering the total energy expended in daily training and living. This is an important issue because a proper nutritional state supports optimal recovery. In addition, body weight and body composition can be optimized by utilizing the information on daily energy expenditure. Figure 5 provides an example of the described EE estimation method in fitness and athletic training.

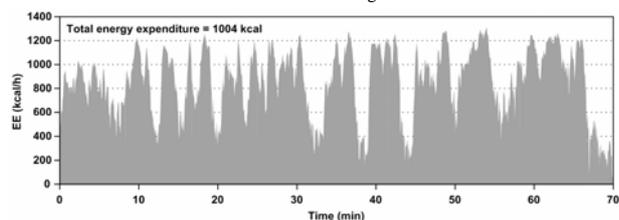


Figure 5. An energy expenditure profile during athletic training.

Research

The described EE-estimation method provides several benefits for research that is targeted to measuring subjects in free-living conditions. Larger number of subjects can be studied simultaneously since only heart rate measurement is needed, with no individual calibration. Although the presented method does not replace the need for laboratory-level evaluation, the method provides near-to-laboratory level accuracy and therefore helps to extend laboratory measurements to the field conditions. In research the methods are preferably applied in combination with laboratory testing (e.g., VO₂max), which provides the best available accuracy for ambulatory studies.

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