Validating the Use of Heart Rate Variability for Estimating Energy Expenditure

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Abstract
The ability to measure free-living and activity-specific energy expenditure (EE) is useful for a variety of purposes. Heart rate variability (HRV) monitoring is emerging as a means for estimating EE and other physiological measures. The purpose of this study was to assess the accuracy of HRV-derived EE across a range of physical intensities and during free-living. Participants (n=30) completed two treadmill tests (walk and VO₂max) measuring EE via Indirect Calorimetry (IC) and with the FirstBeat Bodyguard HRV monitor. Participants also wore the HRV monitors continuously for four consecutive days under free-living conditions. During the walk test, HRV-EE estimates across analysis conditions correlated moderately with IC estimates of EE (r=0.60-0.75; p<0.05). During VO₂max testing, HRV-EE estimates across analysis conditions correlated strongly with IC estimates of EE with (r=0.85-0.98; p<0.05). During free-living conditions, daily average and 4-day total HRV-EE estimates across all analysis conditions correlated strongly (r=0.75-0.98; p<0.05). HRV-EE estimation improves as activity-intensity increases. HRV-EE estimates improve further with the addition of IC-measured HRmax and VO₂max, particularly at low intensities; however, meaningful differences were not seen between values when considering group means. HRV-EE estimates are sufficiently accurate to indicate this method possesses practical utility and may be used for individual EE monitoring.

Keywords
Heart Rate Variability, Indirect Calorimetry, Maximum Heart Rate, VO₂max, Activity Intensity

1. Introduction
The ability to assess an individual’s energy expenditure (EE) is useful in a multitude of athletic-, lifestyle-, and health-related scenarios. For athletes performing intense training on a daily basis, EE monitoring can provide valuable information to optimize energy intake and training duration, intensity, and frequency to promote peak performance while avoiding overtraining. Individuals with inactivity-related health issues, or those seeking to improve their health, can also benefit from daily EE monitoring by tracking physical activity patterns and tailoring energy intake accordingly. However, EE monitoring can only be beneficial if the chosen method of measurement is reliable and accurate.

Generally, EE assessment can be accomplished using several different methods of measurement and analysis including: direct (DC) and indirect (IC) calorimetry, doubly labelled water (DLW), heart-rate (HR), accelerometers, activity diaries and most recently, heart-rate variability monitors. DC and IC are considered the most accurate methods of assessment [3, 12, 13], however they require costly laboratory equipment and expertise. Doubly labelled water is the most accurate free-living assessment of EE, however this method is only capable of measuring block-periods of EE (e.g. 48h), does not allow for activity-specific EE analysis and is not readily accessible for use [2, 3]. Accelerometers and activity diaries are the least expensive methods, but their accuracy in field studies has been questioned [3, 9, 11].

The use of HR devices for estimating EE has become mainstream in the last decade, particularly for use in athletes, both professional and amateur. The added advantages of these devices are that they allow for free-living data collection and the determination of activity-specific EE while being more cost-effective than IC, DC and DLW, and more accurate than accelerometers or diary records [9]. This is based upon the linear relationship between heart rate and kilocalorie expenditure at sub-maximal exercise intensity, making HR measurement a good surrogate measure for EE estimation [2, 5, 14]. Adding to the appeal and versatility of HR-based EE estimation is the ability to obtain reasonably accurate EE measurements without the need for individual calibration of the monitoring device. Rennie, et al. [16] compared EE values obtained from HR monitoring of subjects over 4-days and found that the values obtained with and without individual device calibration were highly correlated. The ability to obtain accurate EE measures...
without the need for device calibration, beyond inputting basic personal information (age, height, weight, activity level), is appealing because the testing necessary to obtain the measures for full device calibration (i.e. maximal HR (HR_{max}) and maximal oxygen consumption (VO_{2max})) requires an individual to exercise at high intensity and may be contra-indicated for individuals with existing health concerns.

To date, studies have shown over-estimation of EE using traditional HR methods in comparison to gold-standard measures [5, 7]. To address this, FirstBeat Technologies Ltd. [8] (among others) developed a Heart Rate Variability (HRV) monitor and analysis software. This device acts like an electrocardiogram, continuously recording the variation of beat-to-beat intervals, also known as R-R intervals. The FirstBeat Software developed for use with this device then utilizes the HRV data, as well as information about respiration rate and On/Off response kinetics of VO2 derived from R-R-interval, to estimate EE [8]. This is more accurate than HR estimation alone [14].

HRV measurement has the additional benefit of being able to provide information regarding parasympathetic and sympathetic nervous system input on HR, and it can be used to extrapolate information regarding disease risk, stress, recovery, activity intensity, training effect, and energy expenditure [1, 2, 8, 18]. These applications hold promise for extended use of these devices, (i.e. outside of sport) in general population for the purposes of exercise prescription, health maintenance, physical capacity assessment, and activity monitoring.

Montgomery et al. [14] first investigated the accuracy of the HRV system, using data obtained from a Suunto HR device analyzed in Firstbeat Technologies software, to estimate EE compared to IC during sub-maximal and maximal intensity exercise on a treadmill. Their study showed improvement of EE estimation across the three levels of analysis at moderate to high intensities compared to HR estimations, however all analyses showed an underestimation of the EE compared to IC. They argued that accuracy is primarily lost at maximal intensities and that inputting measured maximal HR and VO_{2max} significantly improved accuracy. This particular study however focused solely on trained athletes and only evaluated EE derived from the HRV data against IC at moderate-to-high intensity activity.

To date, investigation of HRV-based EE estimation in comparison to IC during low intensity activity and daily living in non-athlete participants has never been done. Considering the potential applications of the FirstBeat Bodyguard, the accuracy and performance of the device across a full range of physical intensities needs to be studied in order to validate its accuracy and in turn its use as a practical tool for estimation of EE in a variety of settings and contexts.

For the benefits of EE monitoring to be applied within the general population for the purposes of exercise prescription, health maintenance, physical capacity assessment, and activity monitoring, it is crucial that the device used be:

user-friendly, mobile, and comfortable under every-day living conditions. Additionally, it should be capable of individual-calibration, based on estimates, without the need for gold standard laboratory measures, specifically for VO_{2max} or HR_{max}, while still providing accurate EE measurements. An important consideration for the expanded use of this technology is whether or not it is necessary to obtain measured maximum/minimum Heart Rate (HR) and maximum oxygen consumption (VO_{2max}) values in order to individually calibrate the device and software for EE calculation. These two measures require the subject to exercise at increasing intensities (often on a treadmill) until exhaustion. Due to these requirements they maintain an inherent level of risk, specifically for a heart attack, and therefore are only performed in clinical or laboratory settings. Even under these conditions, some people would be excluded from performing these tests as a precaution. However, using less invasive means, we can estimate an individual’s HR_{max} and VO_{2max}. EE has been found to be reasonably estimated without individual calibration of HR monitoring devices [16], however it has yet to be determined if individual calibration using measured HR_{max} and VO_{2max} is a necessity for accurate EE measurement using the FirstBeat Bodyguard HRV device and analysis software. EE monitoring during physical activity and daily-living, in conjunction with dietary caloric restriction, is a useful tool for achieving weight loss and long-term maintenance of a healthy weight [6] but it is important to ensure that a device chosen for this and related purposes does not provide inaccurate EE estimates.

Therefore, the purpose of this study is threefold: i) to compare the EE estimates of the FirstBeat HRV monitor during low intensity exercise (i.e. 30 minute walking) with EE measured using Indirect Calorimetry; ii) to compare the EE estimates of the FirstBeat HRV monitor during maximum intensity exercise (i.e. VO_{2max} test) with EE measured using Indirect Calorimetry; and iii) to compare EE estimates under conditions of daily living, as calculated using measured (with Indirect Calorimetry) versus estimated (standard estimates and FirstBeat measured estimates) of HR_{max} and VO_{2max}.

2. Materials and Methods

Participants

Thirty adult participants consented to be involved in this study. All were healthy, non-smoking and non-elite athletes. Participants were screened using the PAR-Q [4] and a general Health Status form to assess their capacity to safely perform a VO_{2max} test. If any contraindications were identified on either form, the participant was excluded from the study; however no one was excluded for this reason. During laboratory testing and analysis, 6 participants were removed from the study due to missing HRV data during the low intensity and/or maximum intensity treadmill testing, resulting in a total of 24 participants (12 females, 12 males).
Missing data resulted from detachment of the electrode due to excess sweat as well as from loss of connection between the electrode cables and the HRV data logger.

Upon completion of the laboratory testing, the participants continued wearing the HRV monitors for an additional four days of data collection. Seventeen participants (10 females, 7 males) returned the devices with four full days of data that were available for analysis. The other 13 participants either had large gaps in their HRV data due to periodic device removal, or they did not return the devices with four full days of data; therefore they were not included in the free-living data analysis. This study received approval from the Laurentian University Research Ethics Board and all participants provided written consent prior to commencing the study.

**Laboratory Study Design**

Participants visited the laboratory once for approximately 90-minutes. Preliminary test measures were taken: age, height, weight, and resting heart rate (HRrest). After this, each participant completed two consecutive treadmill-based tests, separated by a 2-minute break: 1) a 30-minute, low intensity walk test; and 2) a high intensity, maximal oxygen consumption (VO₂max) test. Participants wore the FirstBeat Bodyguard heart rate variability (HRV) monitors, as per manufacturer instructions, throughout testing as well as having their oxygen consumption continuously measured using a SensorMedics Vmax-29c metabolic cart.

Maximum heart rate (HR max = beats per minute) was calculated by two methods: i) estimated HRmax using Tanaka et al. [17] (208-(0.7*age = HRmax); and ii) measured HRmax via the FirstBeat Bodyguard 2 during the high intensity test (HRmaxM).

Maximal oxygen consumption (VO₂max = ml/kg/min) was calculated through two methods: i) estimation using fitness activity classifications (0-10) as described in the FB Sport Software program (VO₂maxFB); and ii) measured using the SensorMedics Vmax-29c metabolic card during the high intensity test (VO₂maxIC).

Using various combinations of these measures, EE values were compared across four conditions: i) obtained from IC measures (EEIC) - walk test and high intensity tests only; ii) obtained from the FirstBeat SPORT (FB) software using estimated HRmax and activity class (EE1); iii) obtained from the FB software using measured HRmax and VO₂maxFB (EE2); and iv) obtained from the FB software using measured HRmax, and VO₂maxIC (EE3). Table 1 summarizes the four different comparison conditions of measuring or estimating EE.

**Table 1.** Comparison conditions for measuring and estimating EE

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
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<tbody>
<tr>
<td>EEIC</td>
<td>Output from indirect calorimetry</td>
</tr>
<tr>
<td>EE1</td>
<td>FB software w/ age-predicted HRmax and activity level (0-10)</td>
</tr>
<tr>
<td>EE2</td>
<td>FB software w/ measured HRmax and VO₂maxFB</td>
</tr>
<tr>
<td>EE3</td>
<td>FB software w/ measured HRmax and VO₂maxIC</td>
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**30-minute Low-intensity Test**

The participants walked at a speed that was set such that it would elicit a heart rate of between 20-39% of the participant’s heart rate reserve (Target HR = %*(HRmax-HRrest)+HRrest), which is indicative of a light-intensity exercise [15]. This information was established for each individual participant in advance of the testing and monitored for the duration of the testing by a member of the research team through the use of a Polar FT7 HR monitor. Following the low-intensity treadmill test, the participant was given a two-minute break prior to commencing a VO₂max test.

**VO₂max Test**

As described in the Physiology of Exercise (1984) and outlined here, the participant started with a 5-minute warm-up at a moderate walking speed with no gradient. The test was performed in stages of 2-minutes, with speed and/or gradient increasing at the beginning of each successive stage. Each 2-minute stage length provided sufficient time to attain steady-state values. The increases in speed and gradient at each stage ranged from 0.1-1.5 mph and 0-10% respectively. HR was recorded throughout the procedure using the Polar FT7 HR monitor as a safety precaution, to ensure heart rate remained below each participant’s estimated maximum heart rate as previously indicated. The test continued until VO₂ consumption plateaued with increasing exercise intensity indicating the limit at which no further increase in oxygen consumption can occur [10]. Once the exercise test was voluntarily terminated due to exhaustion, the speed and gradient on the treadmill was reduced to a walking speed with no gradient, for a five-minute cool-down period. Multiple members of the research team were present throughout the test to ensure the safety of the participants.

**Daily Free-living**

Participants that wore the HRV device for the extended data-logging period did so commencing after the laboratory session. The devices were worn continuously, except when removed for hygiene purposes and to replace electrodes. Following four consecutive days of wear, participants returned the devices to a member of the research team.

**Data Analysis**

Data collected from the FirstBeat HRV monitors was imported into the FirstBeat SPORT computer software program for analysis. EE expenditure was calculated in four ways for the low and high intensity tests: i) EEIC (the gold standard), EE1, EE2 and EE3. During the 4-day wear period of Active Living Conditions, EE expenditure, was calculated in three ways: EE1, EE2 and EE3.

All data was recorded as the mean plus/minus the standard error of the mean (SEM). The EE data from the metabolic cart (EEIC) was compared to EE calculated using data from the Firstbeat Bodyguard 2 HRV devices analysed in the Firstbeat SPORT software under the aforementioned
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conditions: EE_1, EE_2, & EE_3. Bland Altman plots, created using SigmaPlot 13, indicated that the variance in the measures across all software analysis conditions was within a reasonable range (±2SD) for further statistical analysis (Figures not shown). Paired t-tests, intraclass correlations, and descriptive statistics were used to detect meaningful differences and consistency between the measures. The EE data for each day of the 4-day free-living period was calculated using the Firstbeat SPORT software under the same conditions (EE_1, EE_2, & EE_3) and compared collectively (17 participants x 4 complete days of data = 68 individual days of data). All statistical tests were performed using SPSS version 20.0 and significance was accepted at p<0.05.

3. Results

Average age, height, and weight (±SD) of the 24 participants with intact data for the laboratory tests were: 22±2.3 years, 174±8.9cm, and 71±10.2kg respectively.

HR_max measured and predicted; and VO_2max values measured from FB and IC correlated modestly, but significantly (see Table II).

<table>
<thead>
<tr>
<th>Table 2. Average measured (IC) and predicted (FB) values of participant laboratory testing (n=24) using basic information for HR_max and VO_2max</th>
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<tbody>
<tr>
<td>HR_maxP bpm ± SD</td>
</tr>
<tr>
<td>193±1.6</td>
</tr>
<tr>
<td>VO_2maxFB ml·kg⁻¹·min⁻¹ ± SD</td>
</tr>
<tr>
<td>46.7±6.4</td>
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HR_maxP = estimated maximal heart rate using age-based equation  
HR_maxM = measured maximal heart rate during the VO_2max test  
VO_2maxFB = maximal oxygen consumption estimated by FirstBeat SPORT software during the VO_2max test  
VO_2maxIC = maximal oxygen consumption measured by Indirect Calorimetry during the VO_2max test  
bpm = beats per minute

Figure 1. Average Kilocalorie expenditures during the low-intensity walk test as estimated by EEIC, EE1, EE2, and EE3
Low-intensity Walk Test

During the 30 minute low-intensity test, average EE values (±SE) were: EEIC: 168±11.4 kcal; EE1: 167±10.3 kcal; EE2: 161±9.4 kcal; and EE3: 158±8.9 kcal. Paired t-tests indicated no significant differences between EEIC and any of the FB analysis conditions.

EEIC correlated significantly (p<0.05) with all FB analysis conditions (see Figure 1). When comparing correlations amongst the three FB analysis conditions, EEIC correlated most closely with EE3 (see Figure 1).

Maximum Intensity VO$_{2\text{max}}$ Test

In the maximum intensity VO$_{2\text{max}}$ test, average EE values (±SE) were: EEIC: 168±14.2 kcal; EE1: 178±14.7 kcal; EE2: 170±13.8 kcal; and EE3: 168±13.7 kcal. Paired t-tests indicated no significant differences between EEIC and any of the FB analysis conditions.

EEIC correlated significantly (p<0.05) with all FB analysis conditions (see Figure 2). When comparing correlations amongst the three FB analysis conditions EEIC correlated most closely with EE3 (see Figure 2).

Daily Free-living Energy Expenditure

Average age, height, and weight of the participants with 4 full days of data (n=17, 68 total days) were: 22±2.6 years; 172±9.3 cm; and 68±9.5 kg respectively.

Measured and predicted HR$_\text{max}$ correlated weakly, and VO$_{2\text{max}}$ values measured from FB and IC correlated moderately (see Table III).

During the four-day data collection period, average values for the individual sample days (±SE) (n=68) were: EE1: 2681±80.04 kcal; EE2: 2626±73.57 kcal; and EE3: 2568±68.45 kcal. Paired t-tests indicated significant differences between EE1 & EE2 (p=0.001), and between EE1 & EE3 (p=0.011). EE1 correlated significantly with EE2 (r=0.983; p<0.0001) and EE3 (r=0.844; p<0.0001).

Four-day total values (±SE) (n=17) were: EE1: 10,724±544.1 kcal; EE2: 10,506±491.2 kcal; and EE3: 10,273±451.7 kcal. Paired t-tests indicated no significant differences between EE1 & EE2 (p=0.061), nor between EE1 and EE3 (p=0.198). EE1 correlated significantly with EE2 (r=0.983 p<0.0001) and EE3 (r=0.788; p<0.0001).
4. Discussion

The information that can be extrapolated from HRV monitoring is appealing for a variety of both clinical and athletic purposes. Therefore various groups including hospitals, sports teams, and researchers have begun implementing these devices for various causes, including energy expenditure monitoring.

Implementation within the general population has occurred with the elimination of laboratory measures of VO$_{2\text{max}}$ and HR$_{\text{max}}$. Montgomery et al. [14] showed that these values are important in order to obtain accurate estimates, although this study was in a small population of elite athletes and during high intensity testing. In order to advocate for the use of HRV-based EE estimations outside of these limited circumstances, it is important to further examine its capabilities under more varied conditions and in non-elite athletes to better understand the accuracy of its outputs.

The FirstBeat SPORT software is capable of analyzing HRV data to obtain EE values using various levels of subject baseline information, each increasing in the level of information detail, which informed the decisions surrounding the particular levels of analysis that were chosen for comparison in this study. EE$_1$ is the most basic level of analysis capable by the FirstBeat SPORT software and uses subject age, height, weight, HR$_{\text{rest}}$, HR$_{\text{maxP}}$, and activity level (0-10) to estimate VO$_{2\text{max}}$ via the software’s energy expenditure algorithm (VO$_{2\text{maxFB}}$). This level of analysis would be utilized in the event an individual is deemed physically unable to perform the testing required or does not have access to the equipment and personnel to obtain HR$_{\text{max}}$ and VO$_{2\text{max}}$ values. Thus, this level of analysis is of particular interest since it does not require any testing to be performed for individual device calibration; if, the EE estimates are sufficiently accurate in comparison to IC. EE$_2$ was the next level of analysis chosen for comparison to IC and substitutes HR$_{\text{maxP}}$ with HR$_{\text{maxM}}$, as well as substitutes activity level with VO$_{2\text{maxFB}}$. EE$_3$ was selected based on the scenario wherein an individual is deemed capable of performing maximal exertion activity, but does not have access to the equipment required to obtain VO$_{2\text{max}}$ from gold standard methods of measurement (i.e. indirect calorimetry). In this analysis condition, individual device calibration would be completed by the subject performing a maximum intensity test while wearing the device and obtaining VO$_{2\text{maxFB}}$ from a preliminary analysis of the HRV data (i.e. EE$_1$). EE$_3$ was the final level of analysis selected for comparison to IC and substitutes VO$_{2\text{maxIC}}$ for VO$_{2\text{maxFB}}$. This level of analysis uses participant information obtained from gold standard measures, and is therefore that which most closely replicates the IC analysis conditions using the FirstBeat SPORT software.

To determine whether EE derived from the various levels of HRV analysis is accurate compared to Indirect Calorimetry, intra-class correlations and bland-altman plots, paired t-tests, and descriptive statistics (mean and percentage differences) were used to look for meaningful differences and consistency between the methods of measurement. Correlation coefficients were interpreted as follows: r<0.35=low/weak correlation; 0.36<r<0.67 moderate correlation; 0.68<r≤1.0=high/strong correlation [19].

A key purpose of this study was to establish whether or not it is necessary to obtain HR$_{\text{max}}$ and VO$_{2\text{max}}$ baseline measures prior to the use of HRV devices to monitor individuals during free-living activity. This was necessary and important to determine since testing to obtain these values is invasive, costly and cannot be conducted in many at-risk populations. A moderate, but significant, correlation was found between measured and predicted HR$_{\text{max}}$ and VO$_{2\text{max}}$ (r=0.441; p<0.05 and r=0.493; p<0.05 respectively), and significant difference was found between measured and predicted HR$_{\text{max}}$ (p=0.045), but not between estimates of VO$_{2\text{max}}$ (p=0.680), using paired t-tests. Interestingly, the difference in means between measured and predicted HR$_{\text{max}}$ and VO$_{2\text{max}}$ values (2.1% and 1.3% respectively) was minimal, indicating that estimation accuracy improves when considering groups of subjects. While the FirstBeat software does not predict HR$_{\text{max}}$ and VO$_{2\text{max}}$ accurately enough on an individual level to justify substituting HRV-based estimations of these values for those from IC; estimation of HR$_{\text{max}}$ and VO$_{2\text{max}}$ improves in relation to gold standard values at the group level.

In this study, we compared the use of HRV devices for energy expenditure estimation under three conditions: a low intensity walk test, a maximum intensity VO$_{2\text{max}}$ test, and during extended conditions of daily free-living.

During low-intensity activity, underestimation of EE and moderately strong intra-class correlations were found using the FirstBeat software HRV analysis in comparison to gas-exchange EE estimations (see Figure 1). While the baseline level of HRV analysis (EE$_1$) was found to only correlate moderately with EE$_{\text{IC}}$ (r=0.598), the strength of the correlation did increase meaningfully when adding measured HR$_{\text{max}}$ and VO$_{2\text{max}}$ into the FB software (EE$_3$) (r=0.722). The correlations between EE measures during low-intensity activity were not as strong as would be desired, however support for the similarity between the measures comes from the fact that no significant differences were detected using paired t-tests, and there were only 0.66%, 4.09%, and 6.13% differences between the means of EE$_{\text{IC}}$ and EE$_1$, EE$_2$, and EE$_3$ respectively. Based on these results, the use of HRV-analysis in place of IC during low-intensity activity is warranted, however it is recognized that EE outputs are likely slightly less than actual values. However, the differences do not appear to be large enough to alter the overall interpretation of the energy demands of the activity being analyzed. These results are consistent with the findings of Montgomery, et al. [14], who also indicated slight underestimation of EE from HRV analysis in comparison to that obtained from IC during moderate to high intensity activity.

During maximum intensity activity, intraclass correlations for the VO$_{2\text{max}}$ test between EE estimations from the FB software and those obtained from gas-exchange analysis
were strong (see Figure 2) and provide support for the use of HRV-based EE estimation, in place of IC, for high-intensity activities. Interestingly, the correlation between EE₁ and EEIC (r=0.844) was essentially the same as that which used the predicted VO₂max from the basic level of analysis (EE₂) (r=0.850). This indicates that allowing the software to perform the analysis with just baseline participant information and predicted HRmax is a suitable option for high-intensity activity analysis. If however measured HRmax and VO₂max values are available, they should be used as the software analysis with those values included (EE₃) provides a stronger correlation with IC (r=0.973). Paired t-tests between the HRV analysis conditions and IC showed no significant differences, and there were only 5.69%, 1.17% and 0.39% differences between the means of EEIC and EE₁, EE₂, and EE₃ respectively, indicating that HRV-analysis is a viable substitute for IC across the full range of physical intensities. Ultimately, the benefits inherent in this technology outweigh its limitations and the data may still be used to provide useful recommendations.

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Conflict of Interest

The authors declare no conflicts of interest.
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editing of the manuscript. All authors read and approved the final manuscript.

REFERENCES


