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A new heart rate variability-based method for the estimation of oxygen consumption without individual laboratory calibration: Application example on postal workers

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Abstract

Traditionally, the estimation of oxygen consumption (VO_2) at work using heart rate (HR) has required the determination of individual HR/VO_2 calibration curves in a separate exercise test in a laboratory (VO_2-TRAD). Recently, a new neural network-, and heart rate variability-based method has been developed (Firstbeat PRO heartbeat analysis software) for the estimation of VO_2 without individual calibration (VO_2-HRV). In the present study, the VO_2-values by the VO_2-HRV were compared with the values by VO_2-TRAD in 22 postal workers. Within individuals the correlation between the two methods was high (range 0.80–0.99). The VO_2-TRAD gave higher values of VO_2 compared to VO_2-HRV (19%) especially during low physical activity work when non-metabolic factors may increase HR. When assessed in different HR categories, the smallest difference (11%), and highest correlations (range 0.83–0.99) in VO_2 between the methods were observed at higher HR levels. The results indicate that the VO_2-HRV is a potentially useful method to estimate VO_2 in the field without laboratory calibration.

Keywords: Oxygen consumption; Heart rate; Heart rate variability

1. Introduction

The assessment of energetic demands of physical jobs and tasks has traditionally been based on measurements of oxygen consumption (VO_2). However, direct measurement of VO_2 in real-life tasks is rather cumbersome and, therefore, attempts have been made to find and suggest more feasible estimation methods (for example ISO-8996, 2004).

Heart rate (HR) can be easily measured, and various techniques have been presented in the literature for estimation of VO_2 from HR recordings (e.g. Li et al., 1993; Spurr et al., 1988). In work physiology, the traditional way to use HR data for VO_2 estimation is to determine the individual HR/VO_2 calibration curve in a separate test in a laboratory, usually on a treadmill or cycle ergometer (Rodahl et al., 1974). A person's HR and VO_2 are determined for varying steady-state work loads and a linear HR/VO_2 regression equation is calculated for each subject. At low activity levels, the HR/VO_2 relationship often deviates from the calibration curve and some methods assume a constant level of VO_2 when HR is low (e.g. the so called HR-flex method) (Spurr et al., 1988). HR/VO_2 relationship is also affected, for example, by psychological factors, ambient temperature, size of active muscle mass, static work, and dynamically changing work intensities (Smolander and Louhevaara, 1998). Especially during recovery phases HR recovers much slower than VO_2 (Bernard et al., 1997; Davies et al.,

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1972). Consequently, use of HR measurements only can lead to overestimates of VO_2 in the same way as VO_2 measurement may underestimate the total job strain on the person. An ideal technique would give information on the total job strain, but also would tease apart the metabolic demands and strains from non-metabolic ones without any separate individual calibration.

Recently, a new neural network-based method has been introduced for the analysis of physical (and mental) workload from R-to-R interval (RRI) recordings during work which does not require individual laboratory calibration between HR and VO_2 (Firstbeat Technologies, 2005). The new method is based on both HR and heart rate variability (HRV) from which the software calculates additional information on respiratory frequency and on/off-dynamics. This information allows avoiding the problems related to non-metabolic increase in HR and inconsistencies in HR/VO_2 relation during dynamically changing work intensities (Firstbeat Technologies, 2005; Pulkkinen et al., 2004). In preliminary studies, the new HRV-based method (VO_2-HRV) has been shown to improve the accuracy of VO_2- and energy expenditure calculation during different exercise and recovery conditions compared with methods using HR only (Pulkkinen et al., 2004, 2005). During simulated real-life tasks in the laboratory (mean HR$\sim$100 beats min^{-1}, mean VO_2 $\sim$13 ml kg^{-1} min^{-1}) the mean absolute error of second-by-second VO_2-calculation decreased from $\sim$4 ml kg^{-1} min^{-1} with the traditional HR-based method to $\sim$2.5 ml kg^{-1} min^{-1} with the new method (Pulkkinen et al., 2004).

The aim of the present study was to examine the applicability of VO_2-HRV in estimation of VO_2 in an occupational field setting. The estimated minute-by-minute VO_2 by VO_2-HRV was compared with the VO_2 estimated by the traditional HR/VO_2 calibration method (VO_2-TRAD) in a sample of postal workers during a normal working day. We expected to see the methods differ in VO_2 estimation especially at low activity levels when the relation between HR and VO_2 is influenced by several factors.

2. Methods

2.1. Subjects

Twenty-two postal workers (13 men, 9 women) were the study subjects. Their work tasks represented varying physical activity levels. Five subjects were in customer service (mainly cashier work), 4 subjects in sorting of mail (letters and parcels), and 13 subjects were delivering mail by car or by foot with a push-cart. The mean (SD) age and body mass index (BMI) for men were 41 (8) years and 27.1 (5.0), and for women 42 (8) years and 29.6 (5.2), respectively. Nine of the subjects were overweight (BMI > 30). Six subjects were smokers, and seven subjects exercised regularly during their leisure-time.

A medical check-up was carried out before the study for each subject. One subject had asthma and high blood pressure, and two others asthma. Their results were treated separately, because their health condition/medication might have had an influence on HR and HRV data. The study was carried out under the ethics and quality control of occupational health services, and subject signed an informed consent.

2.2. Procedures

First on a separate day, an incremental bicycle ergometer test was carried out for each subject for determining the individual HR/VO_2 regression line for VO_2-TRAD calculations. Then each subject's R-to-R (RRI) data were collected over 1 full working day using Suunto t6 HR monitor (Suunto Ltd., Vantaa, Finland) that detects the R–R peaks with an accuracy of 1 ms and allows to store 100,000 RRIs. During that day, the subjects were observed (physical and mental stress) continuously while performing their main work tasks. For the present analysis, we used RRI data over the observation periods, which varied from 64 to 463 min with an average of 232 (SD 123) min.

2.3. Estimation of VO_2 by VO_2-HRV

VO_2-HRV was calculated with Firstbeat PRO heartbeat analysis software version 1.4.1 (information available at: http://www.firstbeattechnologies.com). In addition to HR, the software calculates and takes into account respiratory frequency as well as on- and off-response phases (on/off-dynamics), which are both derived from ambulatory RRI data. On/off-dynamics data are used since HR and VO_2 are known to have different response patterns when intensity of physical activity changes (Bernard et al., 1997; Davies et al., 1972; Pulkkinen et al., 2004).

Basic individual input parameters of the software are age, weight, height, gender, smoking habits and physical activity class (Jackson et al., 1990). From these parameters, the program estimates maximal HR (ACSM, 2001), maximal respiration rate (RespR) and VO_{2max} (Jackson et al., 1990). Maximal HR and maximal RespR are automatically updated from the recorded data if higher values are observed.

The Firstbeat PRO-software first scans the recorded ambulatory RRI data through an artefact detection filter to perform an initial correction of falsely detected, missed, and premature heart beats (Saalasti 2003; Saalasti et al., 2004). The consecutive artefact-corrected RRIs were then re-sampled at a rate of 5 Hz by using linear interpolation to obtain equidistantly sampled time series (for more detailed information, see Saalasti 2003). From the re-sampled data, the software calculates HRV power–frequency spectrum second-by-second using the short-time Fourier Transform method (STFT), a generalization of the stationary Fourier into non-stationary time series analysis (Oppenheim and Schafer, 1989; Saalasti, 2003). The spectrum of HRV signal reveals two major components of spectral power which are important for analysing exercise and recovery: low frequency power (LFP, 0.04–0.15 Hz) and high frequency power (HFP, 0.15–1.20 Hz); the latter corresponding to the respiratory frequency (Martinmäki et al., 2006; Perini et al., 1990; Perini and Veicsteinas, 2003; Tulppo et al., 1996).

The Firstbeat PRO-software determines the respiratory frequency based on HR and power–frequency spectrum of HRV. HR level determines the frequency range where from respiratory frequency is detected, since it is most likely that with high HR level respiratory frequency is also high and vice versa. When the correct frequency range has been selected, respiratory frequency is determined from power spectrum as the frequency of the peak power (amplitude) in the spectrum. On/off-dynamics information is derived by the software based on the changes in HR.

The software calculates VO_2 from HR, respiratory rate and on/off-dynamics information wherein the dependencies between these parameters have been determined using neural network modelling (Firstbeat Technologies, 2005; Kettunen and Saalasti, 2005; Saalasti, 2003). VO_2 estimation flowchart is presented in Fig. 1, and in the present study VO_2 was calculated for each minute of the observation period.

2.4. Estimation of VO_2 by VO_2-TRAD

For the determination of HR/VO_2 calibration curves, each subject performed an incremental exercise test until subjective fatigue on a bicycle ergometer (Ergoline Ergoselect 200 P, Ergoline GmbH, Germany). Throughout the test, HR was measured continuously using t6 HR monitor (Suunto Ltd., Vantaa, Finland), and the HR at the end of each work rate (WR) was used for the analysis. The starting WR was 50 W for 2 min followed by 25 W increments every 2 min.

Linear regression equations were determined for the linear portion of each subject's HR/WR curves. The obtained linear correlations between HR and WR were high (range 0.96–1.00). The VO_2 in $\mathrm{ml\,min^{-1}\,kg^{-1}}$ was estimated from WR with the following linear regression equation: $((10.3 \times \mathrm{WR/body\ weight}) + 3.5))$, where the coefficient 10.3 is the oxygen cost per WR in watts in a minute, body weight in kg, and 3.5 is the resting metabolic rate in $\mathrm{ml\,min^{-1}\,kg^{-1}}$ (Hansen et al., 1987). The individual linear regression equations were used to estimate the corresponding VO_2 in $\mathrm{ml\,min^{-1}\,kg^{-1}}$ for each minute-value of HR registered during the work.

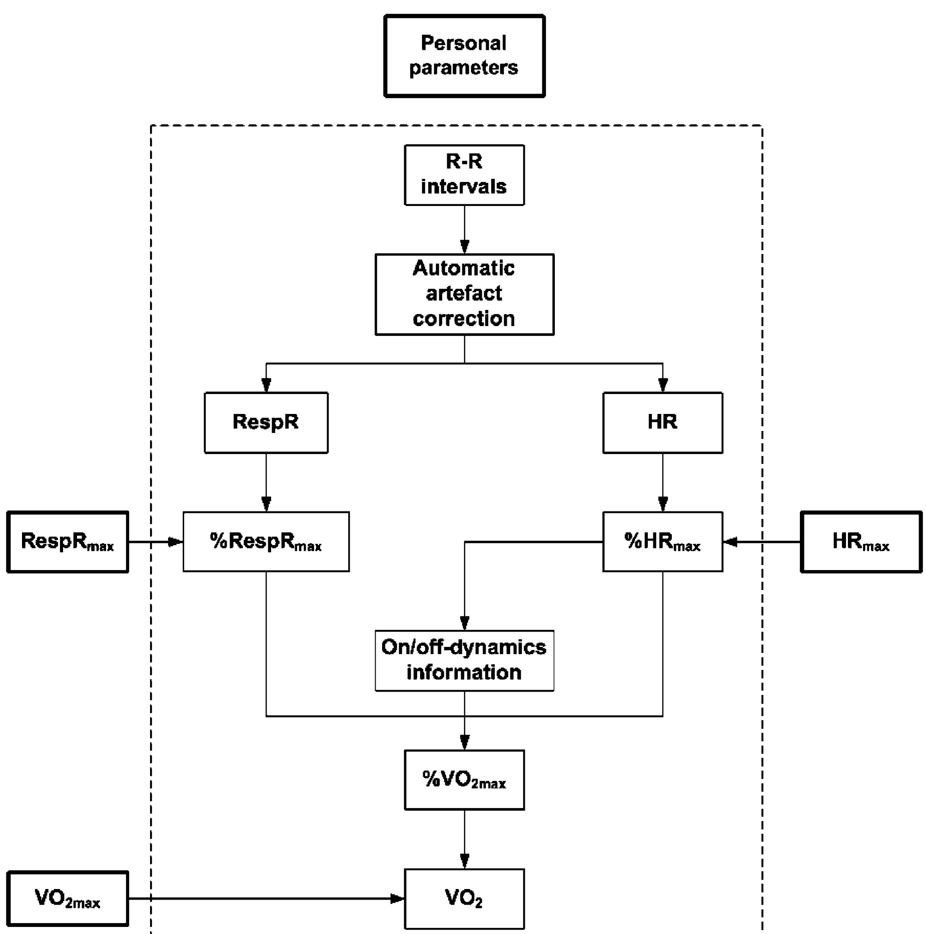

Fig. 1. Model of HRV-derived VO_2 estimation. $VO_{2(max)}$ = (maximal) oxygen consumption, $HR_{(max)}$ = (maximal) heart rate, $RespR_{(max)}$ = (maximal) respiration rate (figure adapted from the White paper at: http://www.firstbeat.fi/files/VO2_Estimation.pdf).

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2.5. Statistics

The association between VO_2-TRAD and VO_2-HRV was determined from the minute-by-minute VO_2 data both at the individual (within-subject) and at the group level (between-subjects). For the between-subjects analysis, each subject's mean VO_2-values from both methods were computed for all recorded HRs and separately for HR categories <80, 80–100, and >100 beats min^{-1}. The differences in VO_2-values between VO_2-TRAD and VO_2-HRV in each of the HR categories were tested by the Student's *t*-test for paired observations. In the within-subject and between-subjects analysis, correlation coefficients were calculated over each subject's whole data, and separately for different HR categories. The results were considered significant when $p<0.05$.

3. Results

Fig. 2 shows an example of one subject's 1-min HR and VO_2 data during the observation period. He was a male worker with a clear overweight (BMI 34.6). His job comprised delivery of mail and parcels to and from companies by car. During the first hour, he was sorting parcels at the office, which was followed by the transport work. The whole work day was quite busy including mostly

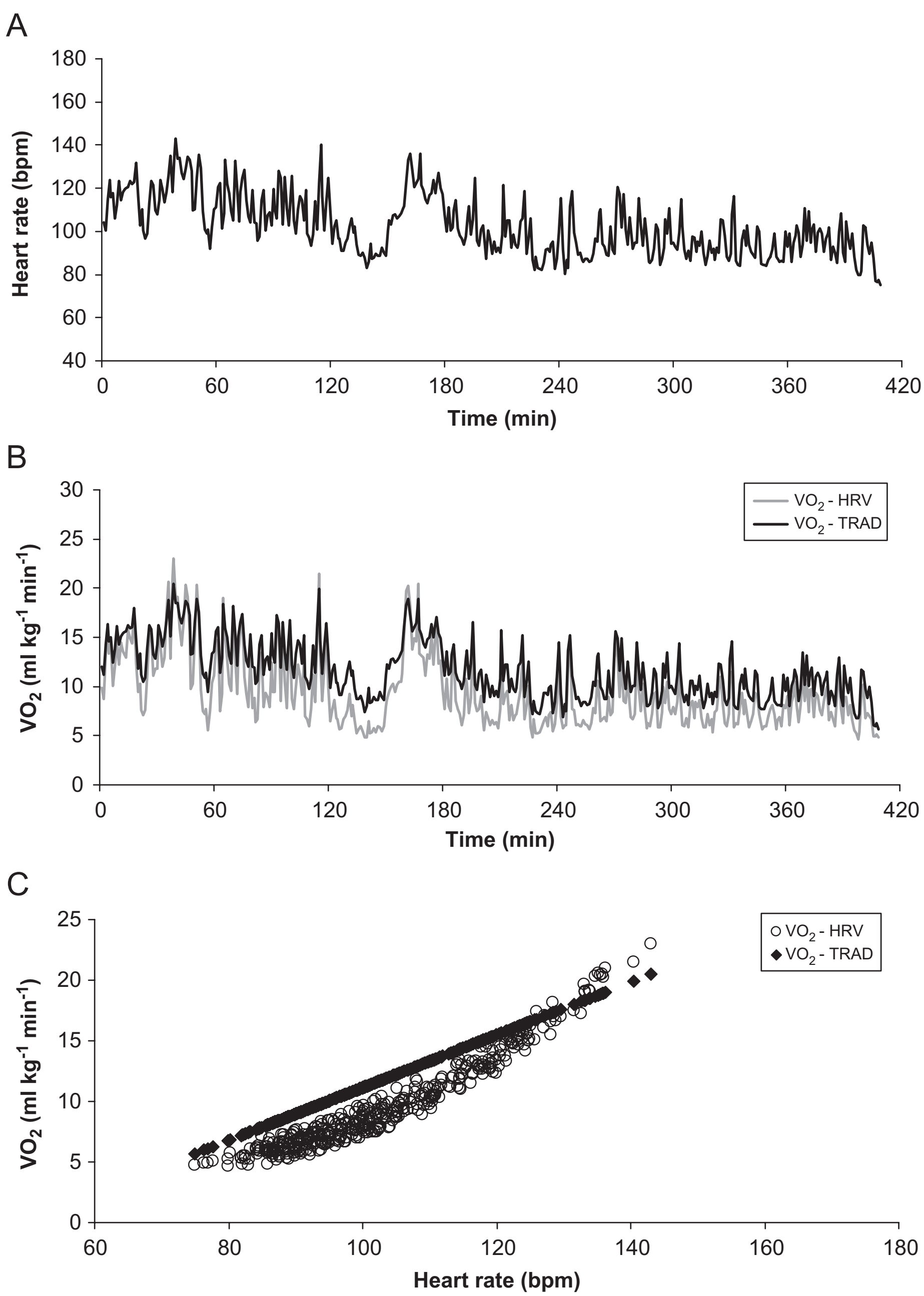

Fig. 2. One subject's minute-by-minute (A) heart rate, (B) oxygen consumption (VO_2) estimated by the traditional calibration method (VO_2-TRAD), and the new method (VO_2-HRV). The lowest panel (C) shows the estimated values as a function of HR.

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Table 1
The average VO_2 (SEM) in different heart rate (HR) categories in postal workers estimated by the traditional HR/VO_2 method (VO_2-TRAD), and with the new method based on heart rate variability (VO_2-HRV)

HR (beats min^{-1})	VO_2-TRAD ($ml\,min^{-1}\,kg^{-1}$)	VO_2-HRV ($ml\,min^{-1}\,kg^{-1}$)	p-Value	r
<80 ($n=14$)	6.0 (0.5)	5.2 (0.3)	0.128	0.36
80–100 ($n=19$)	8.8 (0.4)	6.9 (0.4)	<0.0001	0.67
>100 ($n=13$)	12.2 (0.6)	10.9 (0.9)	<0.05	0.91
All ($n=19$)	9.1 (0.4)	7.4 (0.5)	<0.0001	0.77

r: Correlation coefficient.

intermittent car driving, lifting and carrying. The coffee break after 2 h of work is clearly visible in his HR recording. As shown in the Fig. 1, VO_2-TRAD gives always only one value for each HR, whereas with the VO_2-HRV a single HR reading may indicate different VO_2-value. Furthermore, the expected curvilinear relation between HR and VO_2 is clearly seen in this subject's VO_2-HRV curve. This curvilinearity was observed for all subjects having 1-min HRs over 100 beats min^{-1}. VO_2-TRAD showed a linear relation between HR and VO_2.

During the recording period, the mean of the individual average work HR was 91 (S.D. 10, range 74–113) beats min^{-1}. The total number of minutes analysed was 4509. The majority of 1-min HRs (59%) of all subjects was between 80 and 100 beats min^{-1}, 21% below 80 beats min^{-1}, and 20% above 100 beats min^{-1}, respectively. Five subjects had no 1-min HRs below 80 beats min^{-1}, and, correspondingly, six subjects had no HRs above 100 beats min^{-1} during the recording period.

The means of the individual average estimated VO_2-values for the whole observation period and separately for the different HR levels are shown in Table 1. The VO_2-TRAD gave higher values compared to VO_2-HRV. The overall mean difference was 1.7 $ml\,min^{-1}\,kg^{-1}$ (19%) ranging from -1.1 to 4.3 $ml\,min^{-1}\,kg^{-1}$. The relative difference was smallest (11%) in HR category >100 beats min^{-1}, and highest (22%) in HR category 80–100 beats min^{-1}. The correlation between the estimated values increased with increasing HR (Table 1).

The within-subject correlations between the minute-by-minute VO_2-TRAD and VO_2-HRV values over the whole observation period, including all individual HRs, ranged from 0.80 to 0.99 and averaged 0.93 (S.D. 0.05). The within-subject correlation coefficients in different HR categories increased with increasing HR: below 80 beats min^{-1} the mean correlation was 0.70 (range 0.29–0.90), at 80–100 beats min^{-1}: 0.86 (range 0.74–0.95), and above 100 beats min^{-1}: 0.94 (range 0.83–0.99), respectively.

The differences in estimated VO_2 between the two methods for the three subjects with medication were clearly higher (~5 $ml\,min^{-1}\,kg^{-1}$) compared to the healthy group, but the within-subject correlations between the methods were of similar magnitude (0.91, 0.93, and 0.96) as for the other subjects.

4. Discussion

In the present study, the new HR- and HRV-based VO_2 estimation method was compared with the traditional method requiring separate individual laboratory calibration. In the main, within individuals the correlation between the two methods was high suggesting that it is possible to estimate VO_2 in field setting without laboratory calibration. When assessed in different HR categories, the highest correlations and smallest differences were observed at higher HR levels. However, the VO_2-TRAD gave higher VO_2-values compared to VO_2-HRV. As we expected, the methods differed in VO_2 estimation especially at HR level of 80–100 beats min^{-1}, which is the typical HR zone for most daily activities.

4.1. HR as an estimator of VO_2

When HR is measured at levels varying from rest to moderate-to-heavy activity, often a curvilinear HR/VO_2 relationship is obtained (Dauncey and James, 1979; Moon and Butte, 1996). This curvilinearity was also seen with the VO_2-HRV in the present study. Therefore, in the VO_2-TRAD a regression line obtained from the linear portion of the response may produce significant errors in the estimation of VO_2 at low activity levels (Dauncey and James, 1979). Some authors have suggested calibrating the HR with activities and intensities usually encountered in everyday life (Dauncey and James, 1979; Li et al., 1993; Livingstone et al., 2000; Oja et al., 1982), and then preferably to use continuous non-linear models (cubic, sigmoid, logistic) (Dauncey and James, 1979; Schulz et al., 1989). Some have suggested establishing separate calibration curves for low and high intensities in connection with motion sensor data (Moon and Butte, 1996). Flex HR method assumes a constant level of VO_2 when HR is below the so called flex HR, which has to be determined individually in a laboratory (Spurr et al., 1988). All the above-mentioned improvements have increased the accuracy of HR-based predictions of VO_2, but they require lengthy, complex, and costly calibration procedures, which are not practical to be used, for example, in occupational health care.

4.2. The use of information on on/off-dynamics and respiration

HR/VO_2 calibration procedures assume a steady-state relationship between the variables. However, daily life (as shown in Fig. 1) may include intermittent and widely varying activity patterns, where the cardiorespiratory dynamics have an important role in modifying the HR/VO_2 relationship. During intermittent activity, there is a temporal dissociation between HR and VO_2 and especially during recovery phases HR decreases much slower than VO_2 (Bernard et al., 1997; Bot and Hollander, 2000; Davies et al., 1972). Livingstone et al. (2000) considered this as 'perhaps an intractable problem'. In the new HRV-based method this problem has been solved by utilizing information on respiration and on/off-dynamics analysed from changes in HR and HRV. Respiratory frequency is almost linearly related to ventilation and VO_2 and it decreases similarly to VO_2, i.e. faster than HR after exercise (e.g. Grucza et al., 1990; Short and Sedlock, 1997). The differences after dynamic and rhythmic-static exercises in the recovery of VO_2 and heart rate (Grucza et al., 1990) can also be taken into account when using information on both HR and respiration.

4.3. Factors affecting HR at low activity levels

At low activity levels, prevalent mental strain can also produce 'additional' increases in HR over the levels usually observed with pure physical work (Szabo et al., 1994). In the present sample, self-reported mental strain at work was higher compared to leisure-time (Kinnunen et al., unpublished observations). Consequently, during low-activity physical work psychological factors may induce an overestimation of VO_2 by VO_2-TRAD. Although situational perceived stressors may slightly increase respiratory frequency, that increase is smaller than that induced by physical work load (e.g. Grossman, 1983) allowing the calculation of metabolic cost more accurately with respiratory frequency and HR than with HR only. Additional thermal stress (heat, cold) may also influence HR (e.g. Hebestreit et al., 1995). No marked temperature deviations, however, were observed during the present observation periods. Medication may also induce non-metabolic changes in HR and HRV, and in the present study this influence was obvious in three subjects.

The VO_2-TRAD does not take into account the curvilinear HR/VO_2 relationship, and the temporal dissociation of HR and VO_2 during changing intensities. In addition, when the HR levels were below 100 beats min^{-1}, the postal work tasks were in most cases done at the post office involving upper body and arm work (e.g. cashier, lifting, sorting), whereas higher activity and HR levels were more often connected to dynamic leg work (e.g. carrying, cart pushing, climbing stairs). In the latter case, the difference between the estimated VO_2-values by the methods was reduced, and the correlations were higher than at the lower intensity levels. In static work and in dynamic exercise with arms the HR will be higher at a given VO_2 compared to dynamic leg exercise (Vokac et al., 1975).

Although we did not have direct measurements of VO_2 during the work tasks, the overestimation of VO_2 by VO_2-TRAD during postal tasks was probably a true finding. The mean oxygen cost of bicycle ergometer exercise and, similarly, the mean difference between the two methods would have been the same even though at individual level some differences would have been observed. During the postal work tasks the VO_2 measurement would have influenced the work performance that was not accepted by the workers and their employer. In the preliminary laboratory trials, the VO_2-HRV was more accurate in estimating VO_2 than the traditional methods (Pulkkinen 2003).

5. Conclusions

1. The new VO_2-HRV method is a potentially useful method to estimate VO_2 in field conditions.
2. The VO_2-HRV method may allow easily accomplished precise tracking of detailed changes in VO_2 and energy expenditure without individual laboratory calibration.
3. Further validation studies with different independent settings are needed.

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