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Research article

A comparison between ventilation and heart rate as indicator of oxygen uptake during different intensities of exercise

Steven Gastinger [1]✉, Anthony Sorel [1], Guillaume Nicolas [1], Arlette Gratas-Delamarche [1] and Jacques Prioux [2]

[1] M2S Laboratory, Physiology and Biomechanics, UFR APS University of Rennes 2, 35044 Rennes Cedex, France
[2] ENS – Cachan, Antenne de Bretagne, Campus de Ker-Lann, 35170 Bruz Cedex, France

Abstract

The aim of this study is to compare the relation between ventilation (V_E) and oxygen uptake (VO_2) [$VO_2=f(V_E)$] and between heart rate (HR) and VO_2 [$VO_2=f(HR)$]. Each one of the subjects performed three types of activities of different intensities (walking without load, walking with load and intermittent work). VO_2, V_E, and HR were measured continuously by using indirect calorimetry and an electrocardiogram. Linear regressions and coefficients of determination (r²) were calculated to compare the relation $VO_2 = f(V_E)$ and $VO_2 = f(HR)$ for two different regroupings: by session duration ($r^2_{session}$) and by subject ($r^2_{subject}$). Results showed that $r^2_{session}$ of the relation $VO_2 = f(V_E)$ were significantly higher than those of the relation $VO_2 = f(HR)$ for steady state activities (walking with or without load during 3 or 6 min, $p < 0.01$) and for activities without oxygen consumption steady state (walking with or without load during 1 min, $p < 0.01$ and intermittent work, $p < 0.05$). V_E is more strongly correlated with VO_2 than with HR. This is a very promising approach to develop a new method to estimate energy expenditure.

Key words: Physical activities, light to moderate intensities, steady state activities, non-steady state activities.

Introduction

Physical activity represents the most variable part of the human energy expenditure (EE) (Ravussin and Gautier, 2002). The accurate measurement of EE associated with physical activity remains a difficult challenge. This difficulty increases when we look at light or intermittent activities. Many parameters have been explored to estimate EE, during physical activities of different intensities. Doubly labelled water (DLW) and indirect calorimetry techniques, considered as the gold standard measures of EE (Westerterp, 1999), are both limited in their assessment of free-living EE. Indirect calorimetry cannot assess free-living subjects easily, whereas DLW does not provide information on the pattern, frequency, or intensity of physical activity. Portable and less costly devices are emerging and also making it possible to estimate EE in free-living conditions. Electronic motion sensors attempt to analyze the movements of the human body in order to estimate "counts" and TEE (Total Energy Expenditure) (Bouchard and Trudeau, 2008; Corder et al., 2007; Nilsson et al., 2008; Plasqui and Westerterp, 2007). Unfortunately, they are unable to detect arm movements, or external work done in lifting or pushing objects, which may represent a considerable component of lifestyle activity (Bassett et al., 2000). New portable devices are able to couple biomechanical and physiological parameters. The Actiheart® and the SensorWear Armband® coupled the measurement of physiological parameters (heart rate and heat flow respectively) with an accelerometer system. These devices provide better results compared to the classic electronic motion sensors, but differences are still measured in comparison with reference methods (Brage et al., 2005; Corder et al., 2005; Fruin and Rankin, 2004; King et al., 2004).

To consider EE under free-living conditions, one of the most current approaches in the field of physiology, consists in using the relation between heart rate (HR) and oxygen uptake (VO_2) ($VO_2 = (HR \times V_{es}) \times (CaO_2 - C\bar{v}O_2)$), where V_{es} represents the volume of systolic ejection ($ml \cdot min^{-1}$), CaO_2 is the amount of oxygen carried by arterial blood ($ml \cdot 100ml^{-1}$), and $C\bar{v}O_2$ is the amount of oxygen carried by venous blood ($ml \cdot 100ml^{-1}$). This method has been largely studied (Garet et al., 2005; Hiilloskorpi et al., 2003; Kurpad et al., 2006; Livingstone et al., 2000; Rayson et al., 1995) and proved to be adapted to estimate EE: the cardiofrequencemeter is an easily portable device that does not present any invasive character. Nevertheless, the use of HR to consider EE can be criticized because of the variability of this parameter during activities of low and very high intensities (Achten and Jeukendrup, 2003; Haskell et al., 1993). In the same way, many other studies (Davidson et al., 1997; Melanson and Freedson, 1996; Montoye et al., 1996) have showed that emotional stress, high ambient temperature, high degrees of humidity, dehydration, body posture, or disease may imply HR variations without any VO_2 variation. All these limits account for the difficulties of measuring a precise EE from HR measurements particularly during light physical activities. Therefore, we propose to explore another physiological parameter, complementary to HR, which is also in strong relation with VO_2 and EE.

Ventilatory output or ventilation (V_E) also varies during physical activity (Saltin and Astrand, 1967; Wasserman et al., 1986) and two studies suggest that pulmonary ventilation (V_E) could be an index of EE (Durnin and Edwards, 1955; Ford and Hellerstein, 1959). Indeed, V_E is a parameter directly related to oxygen consumption ($VO_2 = V_E \times [F_iO_2 - F_eO_2]$, where F_iO_2 represents the fractional concentration of O_2 in inspired air and F_eO_2 is the fractional concentration of O_2 in expired air)

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and thus indirectly with EE (Saltin and Astrand, 1967). V_E is especially interesting because Durnin and Edwards report that, during light and moderate exercise, when V_E is less than 50 $l{\cdot}min^{-1}$, VO_2 of any one individual is directly proportional to his V_E.

Furthermore, V_E does not necessarily require the use of a facial mask to be measured. McCool et al. (2002) in this case proposed a light and portable system to measure V_E based on four coupled magnetometers. This system, compared with the measurement carried out by spirometry, enables a precise measurement of tidal volume (V_T), inspiratory (T_I), and expiratory time (T_E) in sitting and standing positions and exercise conditions. Taking into consideration this new technology, it may now be possible to use V_E to estimate EE. Such an approach may therefore provide new prospects in EE estimation, compared with the limitations of HR measurements. Nevertheless, it may be questioned as to which of the two parameters V_E or HR is better correlated with VO_2. The purpose of this methodological study is to answer this question during physical activities of different intensities. Then, we postulate the following hypothesis: during physical activities of different intensities V_E is more strongly correlated with VO_2 than HR. To validate our assumption, we compared the relations $VO_2 = f\,(HR)$ and $VO_2 = f\,(V_E)$ during varied sequences of walking with and without load and intermittent work.

The interest of this work is to compare the parameters V_E and HR as an indicator of VO_2 and to show the interest of V_E to estimate EE. Moreover, it is important to note that this is the first study who choose to compare the two relationship, $VO_2 = f\,(HR)$ and $VO_2 = f\,(V_E)$, during physical activities of different intensities.

Methods

Subjects

Twelve healthy males, aged 27.25 ± 4.33 years, voluntarily took part in this study. The mean values and standard errors of their physical characteristics, maximal oxygen uptake (VO_{2max}), and ventilatory threshold (VT) are shown in Table 1. This study was conducted according to the guidelines laid down in the Declaration of Helsinki and all procedures involving human subjects were approved by the local ethics committee of the University of Rennes 1. Written informed consent was obtained from all subjects. None of the subjects reported respiratory or cardiac disease, hypertension, or was known to be suffering from any other chronic disease.

Experiment design

The experimental protocol is schematized in Figure 1. The first day of experiments (D1) was devoted to laboratory testing, including anthropometric and body composition measures. Each subject performed a maximal

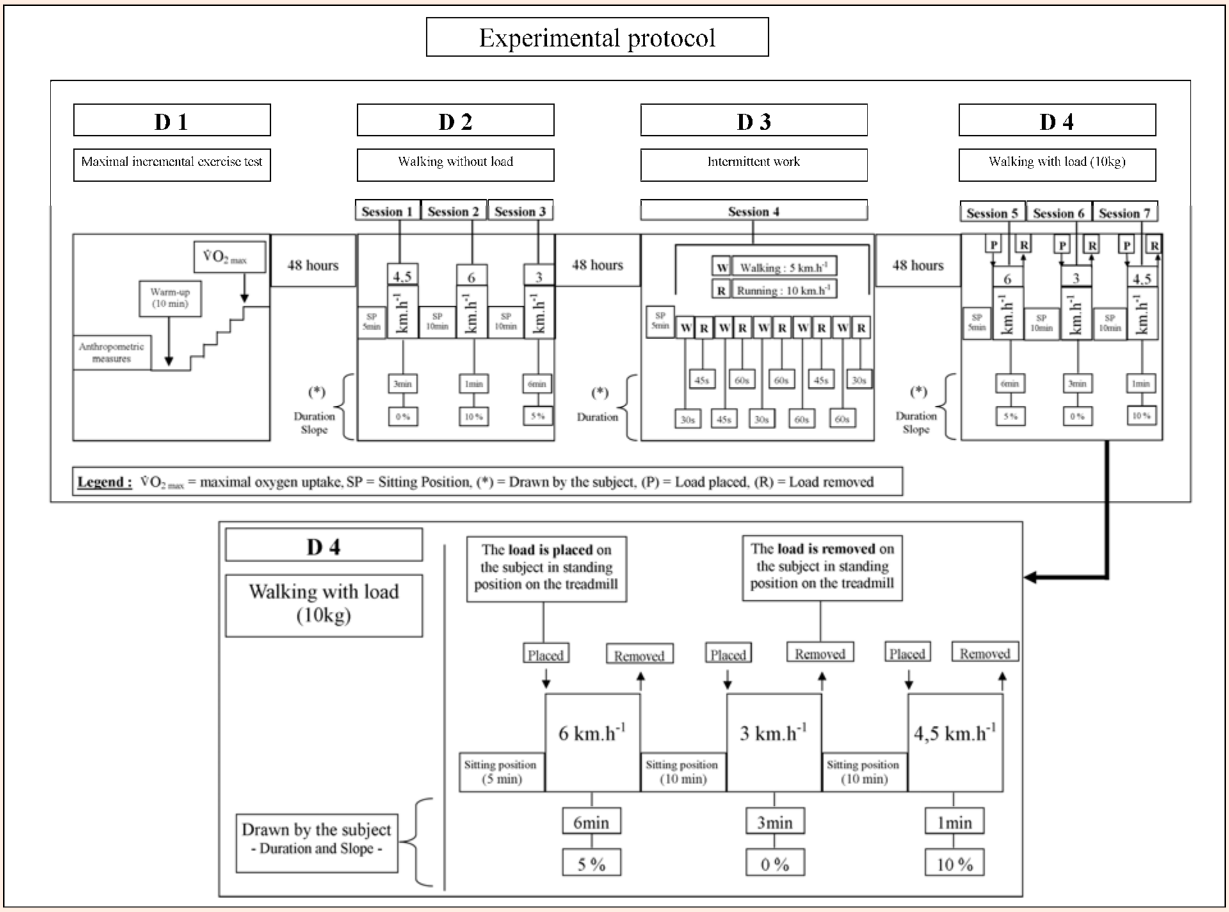

Figure 1. Description of the four days (D1, D2, D3 and D4) and details of the activity "walking with load" (example of the experimental protocol of the subject n°4).

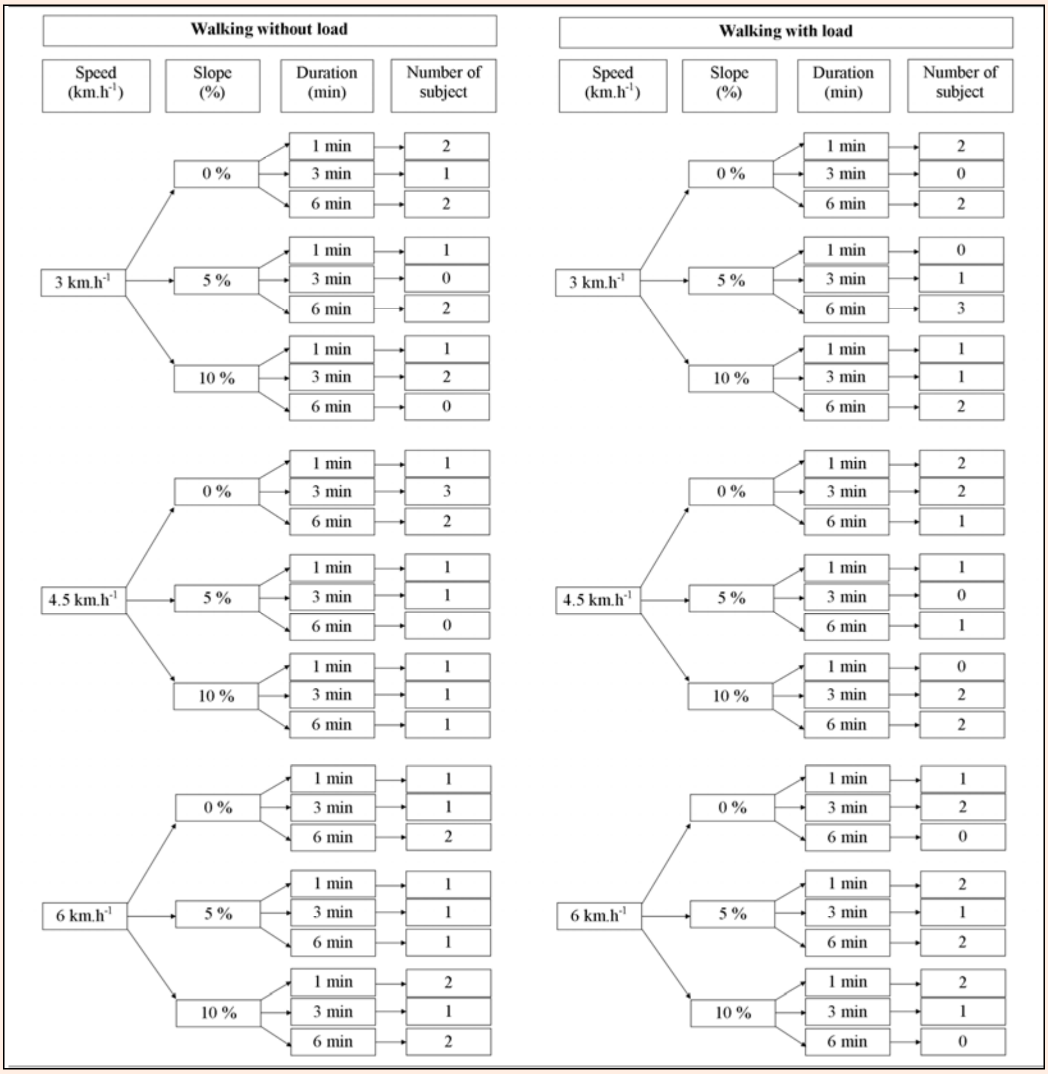

Figure 2. Details of the experimental protocol: walking with and without load (68 walks).

increment exercise test on the treadmill in order to appreciate the relative intensities of each exercise carried-out on D2, D3 or D4. A warm-up session was carried out for 10 min at 8 km·h^{-1}. The test started at an initial 10 km·h^{-1}. The incrementation of the test was 1 km·h^{-1} every 3 min. The subjects were verbally encouraged to continue their efforts. It was estimated that the subjects had reached their VO_{2max} when three or more of the following criteria were met; a steady state of VO_2 despite increasing running speed (change in VO_2 at $VO_{2max} \leq 150$ ml·min^{-1}) (Taylor et al., 1955), a final respiratory exchange ratio (R_{max}) higher than 1.1, a visible exhaustion and a HR at the end of the exercise (HR_{max}) within the 10 bpm of the predicted maximum [210 – (.65 × age); (Spiro, 1977)]. During the following three days (D2, D3, and D4) each of the subjects performed three different types of activities (walking without load, walking with load, intermittent work) over three distinct days. A period of 48 hours separated each activity. These activities were carried out randomly by each subject. Each day was initialized by 5 min of rest in a sitting position. All these activities were carried out on a treadmill (Gymrol, super 2500).

The first activity consisted in walking without load. Each subject carried out three sessions of walking (3, 4.5, and 6 km·h^{-1}), the order being self-selected by the subject. Thereafter, each walking session was characterized by a time duration (1, 3, or 6 min) and a slope (0, 5, or 10 %) also self-selected by the subject. The detail of the walking session with and without load is presented in Figure 2. One 10-min period of rest (seated) was maintained between each session of walking. The second activity was walking with a load. The protocol was the same as that for walking without a load. The load applied to the subject was a backpack stuffed with 10 kg. The load was applied to the subject at the last minute, right before starting the walking session. During periods of rest and between the various steps, the backpack was removed from the subject. Finally, the third activity was intermittent work. This session consisted in alternating walking (5 km·h^{-1}) and running (10 km·h^{-1}) sequences. A session consisted of five consecutive sequences where the duration of each period of walking and running was chosen at random by the subject (30, 45, or 60 s).

The whole range of activities was carried out under ambient controlled conditions. For all activities, participants were asked to refrain from physical activity, medicine, alcohol, and tobacco 24 h before testing and to refrain from food 2 h beforehand. The Subjects were asked

Table 1. **Physical characteristics, maximum oxygen uptake (VO_{2max}) and ventilatory threshold (VT) data.**

Subjects	Age (yr)	Height (cm)	Weight (kg)	Fatty mass (%)	VO_{2max} (ml.min^{-1}.kg^{-1})	VT(%VO_{2max})
1	32	179	75.6	17.8	59	51.6
2	21	178	80.4	15.3	58	49.4
3	34	176	71.9	17.9	52	46.8
4	27	184	73.7	7.8	61	53.3
5	27	186	68.3	8.7	62	49.5
6	23	176	76.6	12.4	56	46.6
7	33	179	70.9	16.3	62	47.7
8	31	181	78.7	20.9	54	42.4
9	27	180	76.2	15.3	54	48.5
10	23	171	63.8	12.6	64	56.4
11	24	193	83.3	11.7	58	41.4
12	25	177	71.5	13	56	42.4
Mean	27.25	180	74.2	14.1	58	48
SD	4.33	5.64	5.40	3.85	3.74	4.53

VO_{2max}: Maximum oxygen uptake (ml.min^{-1}.kg^{-1}), % VO_{2max}: Percentage of maximum oxygen uptake, SD: Standard Deviation

to arrive at the laboratory 30 min before the beginning of the measurements. On D1, measurements (VO_2, V_E, and HR) started at the beginning of the warm-up period. On D2, D3, and D4, the measurements started at the beginning of the sitting position period of 5 min.

Gas exchange and heart rate measurements

Breath-by-breath measurements of gas exchange were made using the MetaLyser 3B® (Cortex Biophysic, Leipzig, Germany). Expiratory airflow was measured with a volume transducer (Triple V® turbine, digital) connected to an O_2 analyser. Expired gases were analysed for oxygen (O_2) with electrochemical cells and for carbon dioxide (CO_2) output with the ND infrared analyser. Before each test, the MetaLyser 3B® was calibrated according to manufacturers' guidelines. After a 60-min warm-up period, the CO_2 and O_2 analysers were calibrated against room air as well as a reference gas of known composition (5% CO_2, 15% O_2, and 80% N_2), and the volume was calibrated by five inspiratory and expiratory strokes with a 3-litre pump. Oxygen uptake (VO_2) and ventilation (V_E) were measured and displayed continuously on the computer screen. The electrocardiogram (Delmar Reynolds Medical®, CardioCollect 12) was also continuously monitored at both restful and active periods. Heart rate was derived from the R-R interval of the ECG. The ECG tracing was continuously displayed on the computer screen. The entire data (VO_2, V_E, and HR) during each breath was calculated, and the sampled data transferred breath-by-breath to a PC for immediate display. The recorded data was saved in the internal database of MetaSoft® for a precise performance analysis after the test. The data of VO_2, V_E and HR was averaged every 5 s for statistical analysis.

Determination of ventilatory threshold (VT)

VT was determined on D1 during the maximal incremental exercise test. To determine VT for each subject, we used the criteria of Wasserman (Wasserman et al., 1990): the threshold corresponds to the breakpoint in the V_E / VO_2 relationship, whereas the relationship V_E / VCO_2 remains stable. VT was determined visually by two independent investigators.

Session intensity calculation

To evaluate the intensity of each session, we chose to express it as the mean value of VO_2 and as a percentage of VO_{2max}. The mean value of VO_2 was calculated over the total time of each session. These individual values of VO_2 were then averaged to obtain VO_{2mean} and the percentage of VO_{2max} for each activity group (Table 2). The mean value of V_E and HR were also calculated over the total time of each session. These individual values of V_E and HR were then averaged to obtain $V_{E\ mean}$ and HR_{mean}.

Table 2. **Intensities (VO_{2mean}, % VO_{2max}, $V_{E\ mean}$, HR_{mean}) and coefficients of determinations ($r^2_{session}$) from the relations $VO_2 = f(V_E)$ and $VO_2 = f(HR)$. Data are means (±SD).**

Part 1: Physical activities with oxygen consumption steady state

	Subjects (n = 12)	Intensities: VO_{2mean}	% VO_{2max}	$V_{E\ mean}$	HR_{mean}	$r^2_{session}$: $VO_2 = f(V_E)$	$VO_2 = f(HR)$
Group 1	20 % VO_{2max} < I < 55 % VO_{2max} 20 walks : 3 min	1.45 (.54)	33.4 (10.8)	30.3 (10.2)	96 (18)	.87 (**)	.61
Group 2	17 % VO_{2max} < I < 62 % VO_{2max} 26 walks : 6 min	1.42 (.56)	33.5 (13.1)	30.7 (12.3)	92 (19)	.80 (**)	.50

Part 2: Physical activities without oxygen consumption steady state

	Subjects (n = 12)	Intensities: VO_{2mean}	% VO_{2max}	$V_{E\ mean}$	HR_{mean}	$r^2_{session}$: $VO_2 = f(V_E)$	$VO_2 = f(HR)$
Group 3	13 % VO_{2max} < I < 40 % VO_{2max} 22 walks : 1 min	1.05 (.32)	24.2 (7.6)	23.6 (6.5)	89 (12)	.82 (**)	.63
Group 4	40 % VO_{2max} < I < 60 % VO_{2max} 12 intermittent work	2.02 (.20)	47.1 (4.5)	46.0 (4.7)	114 (13)	.82 (*)	.73

VO_{2mean}: Mean oxygen uptake (l·min^{-1}), SD: Standard deviation, % VO_{2max}: Percentage of maximum oxygen uptake, $V_{E\ mean}$: Mean ventilation (l·min^{-1}), HR_{mean}: Heart rate (beats·min^{-1}), VO_2: oxygen uptake (l.min^{-1}), V_E: Ventilation (l.min^{-1}), HR : heart rate (beats.min^{-1}), I : intensity. * and ** denote $p < 0.05$ and 0.01 respectively.

Table 3. Coefficient of determination ($r^2_{subject}$) from the relations $VO_2 = f(V_E)$ and $VO_2 = f$ (HR), by subject, over the total duration of the seven sessions.

Subjects (n = 12)	Coefficients of determination : $r^2_{subject}$ $VO_2 = f(V_E)$	$VO_2 = f(HR)$
1	.954	.867
2	.854	.917
3	.871	.891
4	.906	.865
5	.879	.784
6	.939	.915
7	.919	.727
8	.928	.814
9	.921	.886
10	.945	.891
11	.874	.720
12	.886	.711
Mean	.906 (*)	.832
Standard Deviation	.033	.078

VO_2: Oxygen uptake ($l \cdot min^{-1}$), V_E: Ventilation ($l \cdot min^{-1}$), HR: Heart rate ($beats \cdot min^{-1}$)

Session distribution of activities at various intensities within four principal groups

Eighty-four sessions were programmed as each subject had to carry out seven activity sessions (three walking activities without load + three walking activities with load + one intermittent work). Nevertheless, four of the sessions were not taken into account, as four of the walking activities of two subjects were removed because of errors of measurement. Therefore the full number of sessions included in this study was 80.

In order to analyse the results, the whole range of activities was classified into two different parts. Each part was devised into two different groups. This classification was carried out in accordance with the duration of each activity (Table 2).

- The part 1 includes activities with oxygen consumption steady state. The first group (Group 1) incorporated walking activities with or without load (n=20) for a duration of 3 min and at an intensity including between 20 and 55% of VO_{2max}. The second group (Group 2) incorporated walking sessions with or without load (n=26) for a duration of 6 min and at an intensity including between 17 and 62 % of VO_{2max}.

- The part 2 includes activities without oxygen consumption steady state. The third group (Group 3) incorporated walking activities with or without load (n = 22) at a duration of 1 min and with an intensity including between 13 and 40% of VO_{2max}. Finally, the fourth group (Group 4) is made up of the intermittent work (n = 12) with an intensity including between 40 and 60% of VO_{2max}.

Coefficients of determination calculation

To confirm our hypothesis (that V_E is more strongly correlated with VO_2 than HR), we proposed to compare the relations $VO_2 = f$ (HR) and $VO_2 = f(V_E)$ during varied sessions of activities, using the coefficients of determination (r^2). The r^2 were calculated by combining the whole of the activities in two different ways. Firstly, for all of the activity sessions (n=80), a linear regression was established between parameters VO_2 and V_E and between VO_2 and HR (n = 160 regressions). The r^2 was calculated over the total time of each session ($r^2_{session}$). For the four different groups, all of the individual values of $r^2_{session}$ were averaged out and are reported in Table 2. Secondly, for each subject (n = 12), the data sets of VO_2, V_E and HR of the seven individual sessions were incorporated. From the value sets of each subject, a linear regression was established between VO_2 and V_E and VO_2 and HR (n = 24 regressions). The r^2 was calculated over the total time of the seven individual sessions of each subject ($r^2_{subject}$). The $r^2_{subject}$ is reported in Table 3.

Statistical analysis

We used the Mann Whitney test to calculate the level of significance of the correlations and to specify if there exists a significant difference between the $r^2_{session}$ from the relations $VO_2 = f$ (HR) and $VO_2 = f(V_E)$ of each group of activities. The same test was applied to calculate the level of significance of the average values of $r^2_{subject}$. Values of $p < 0.05$ were considered significant.

Results

Coefficient of determination from the four different groups of activities (Table 2 and Figure 3)

The mean values of the $r^2_{session}$ from the relations $VO_2 = f$ (HR) and $VO_2 = f(V_E)$ for the four different groups of activities are represented in Table 2. The $r^2_{session}$ of the linear regressions from the relation $VO_2 = f(V_E)$ were significantly higher than those obtained from the relation $VO_2 = f$ (HR) for the first (walking exercise with and without load, between 20 and 55% of VO_{2max} and for a duration of 3 min, $p < 0.01$), second (walking exercise with and without load, between 17 and 62% of VO_{2max} and for a duration of 6 min, $p < 0.01$), third (walking exercise with and without load, between 13 and 40% of VO_{2max} and for a duration of 1 min, $p < 0.01$) and the fourth group of activities (intermittent work, between 40 and 60 % of VO_{2max}, $p < 0.05$).

Figure 3 shows the linear regression from the relations $VO_2 = f(V_E)$ and $VO_2 = f$ (HR) for the four different groups of activities. The graphs joined the whole of data of each group of activities (n = 750, n = 1907, n = 295 and n = 1140 for the group 1, 2, 3 and 4 respectively). The standard error of estimate (SEE) was calculated and mentioned on each graph.

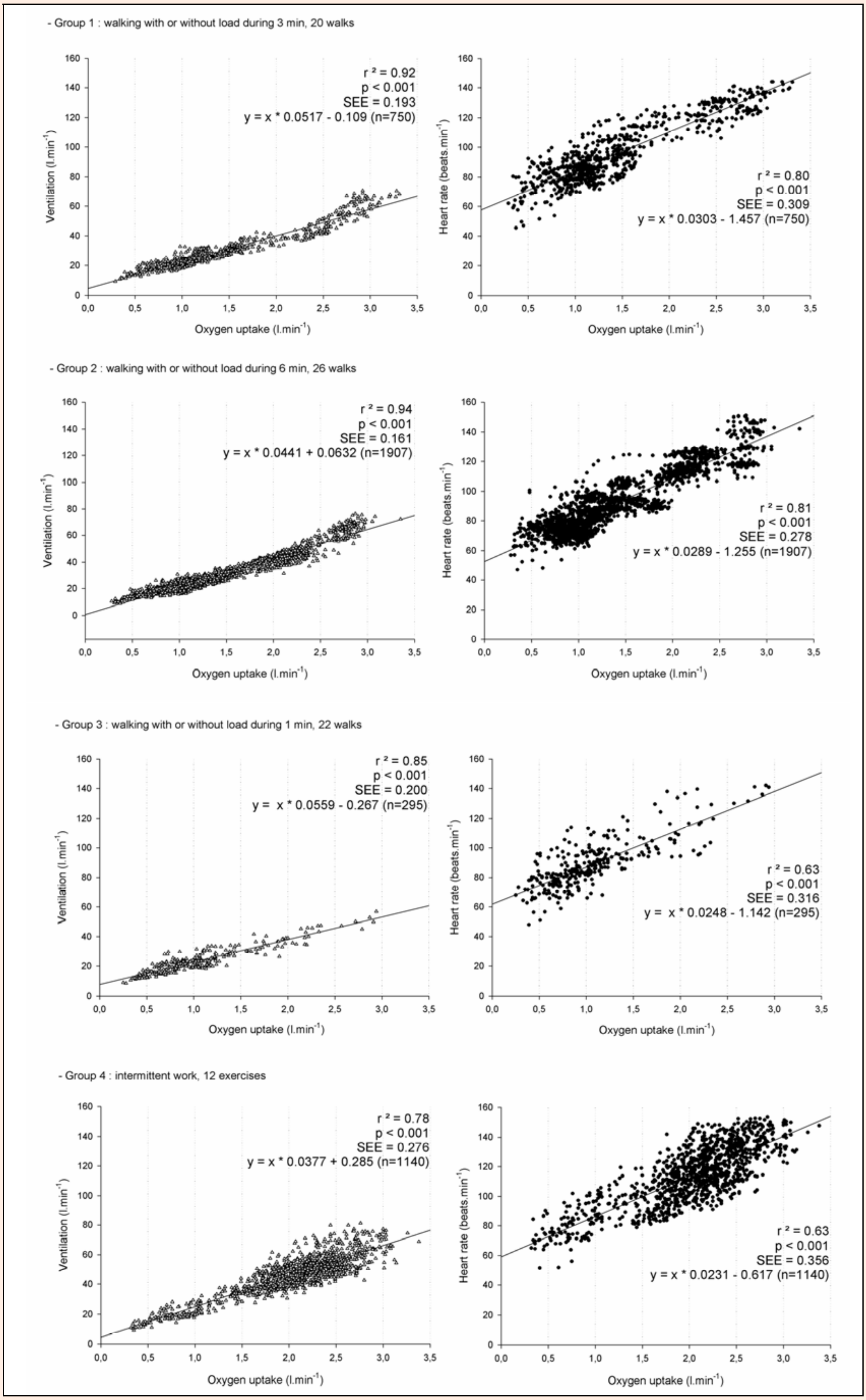

Figure 3. Linear regressions (r², p and SEE) from the relations $VO_2 = f$ (V_E) and $VO_2 = f$ (HR) on the pooled data of the group 1 (walking with or without load during 3 min, 20 walks), the group 2 (walking with or without load during 6 min, 26 walks), the group 3 (walking with or without load during 1 min, 22 walks) and the group 4 (intermittent work, 12 exercises).

Coefficient of determination, by subject, over the total duration of the seven sessions (Table 3)

The individual values of the $r^2_{subject}$ from the relations $VO_2 = f(HR)$ and $VO_2 = f(V_E)$ are represented in Table 3. The $r^2_{subject}$ of the linear regressions from the relation $VO_2 = f(V_E)$ is always higher than those from the relation $VO_2 = f(HR)$, except for the subject 2 and 3. The mean value of $r^2_{subject}$ of the linear regression from the relation $VO_2 = f(V_E)$ was significantly higher than that obtained from the relation $VO_2 = f(HR)$ ($p<0.05$).

Discussion

The aim of this study was to compare the relation between $VO_2 = f(V_E)$ and $VO_2 = f(HR)$ during physical activities of different intensities: walking with or without load, with or without slope during various durations and alternating between different periods of walking and running (Ainsworth et al., 2000). We chose to apply a load of 10 kg to each subject because this weight could correspond to individuals who use a backpack to carry books, computers in free-living conditions. So, we have chosen our exercise protocol because the daily life is characterized by light and moderate activities, carried out in a random order during short durations (Ainsworth et al. 2000). For this reason the walking activities with and without load were characterized by duration and slope self-selected by the subject. The same reasons led us to characterize intermittent work by random duration.

The intensity of each walking exercise and intermittent work was defined from VO_{2mean} calculated on the total time of exercise. This methodology has been observed for all durations of exercise (1min, 3min, 6min and intermittent work). The calculation of VO_{2mean} is coherent with the calculation of the coefficient of determination carried out for each exercise (taking into account the total time of each exercise). However, this approach has constrained us to divide the exercises into two groups. The first group consisted of exercises performed with a VO_2 steady state (walking during 3 and 6 min). The on-transient and steady state period are taken into account to calculated VO_{2mean}. The second group consisted of exercises without oxygen consumption steady state (walking during 1 min and intermittent work). The whole of the variation of VO_2 are taken into account to calculated VO_{2mean}. This calculation is an estimate of exercise intensity. Lastly, we did not seek to calculate the intensity of each walk and each run of the intermittent work.

The range of values of the coefficients of determination ($r^2_{session}$, $r^2_{subject}$) shows that V_E is more strongly correlated with VO_2 than HR (Table 2 and 3). The mean intensities of the sessions are included between 24.2 and 47.08% of VO_{2max}. A light intensity exercise is usually considered at a level between 1 to 3 METs or lower to 45% of VO_{2max}, and a moderate intensity exercise between 3 to 6 METs or lower to 60% of VO_{2max} (Friedlander et al., 2007; Smith and Morris, 1992; Swain and Franklin, 2006). Hence, the results of the study confirm the hypothesis initially posed. Moreover, it is the first study that shows that V_E is more strongly correlated with VO_2 than HR and especially during activities of light to moderate intensities. To validate our assumption, we chose to characterize the relations $VO_2 = f(V_E)$ and $VO_2 = f(HR)$ by a linear regression.

In 1967, Saltin and Astrand showed that during an incremental exercise, the increase of V_E in relation to VO_2 is semi-linear, the progression of V_E becoming relatively more important than VO_2 when the exercise intensities become vigorous. An exponential increase is observed for vigorous intensities of exercises, which are higher than 65% of VO_{2max}. Davis et al. from ventilation criteria observed in subjects, aged 30 years, values of VT of 58.6 ± 5.8% (mean ± SD) of VO_{2max} during a treadmill exercise (Davis et al., 1976). In this study, the intensities of each session of the subjects remain lower than 65% of VO_{2max}. Moreover, the mean intensities of the whole sessions carried out by the subjects are close to than their VT (VT_{mean} = 48 ± 4.53% (mean ± SD) of VO_{2max}). Therefore, the values of V_E and VO_2 remain located in the linear part of the curve. These values of V_E are consistent with the study of Durnin and Edwards who report that, when V_E is less than 50 $l \cdot min^{-1}$, VO_2 of any one individual is directly proportional to his V_E. Indeed, the V_E values are 30.25 $l \cdot min^{-1}$ (±10.22), 30.69 $l \cdot min^{-1}$ (±12.27), 23.64 $l \cdot min^{-1}$ (±6.53) and 46.03 $l \cdot min^{-1}$ (±4.74) for the groups 1, 2, 3 and 4, respectively.

The relation $VO_2 = f(HR)$ is also characterized by a linear relation. This relation is widely accepted for a physical exercise which is progressive, involves important muscular masses, and is long enough to allow adaptation of the cardiovascular and ventilatory systems (Astrand and Ryhming, 1954). Thus, a linear relation exists for a broad range of exercise intensities (classically from 30% to 70% of VO_{2max}), such as those presented in this study (from 24.2 to 47.08% of VO_{2max}). Thus, the values of HR and VO_2 remain located in the linear part of the curve. Nevertheless, during light and very highly intense activity, this relation becomes non-linear (Achten and Jeukendrup, 2003).

To compare our results with other studies (Durnin and Edwards, 1955; Ford and Hellerstein, 1959; Livingstone, Robson, 2000; Spurr et al., 1988), we have, in accordance with these studies, chosen a linear regression to compare the two relations $VO_2 = f(V_E)$ and $VO_2 = f(HR)$, for the whole sessions carried out with the subjects in this study.

The most interesting result of this study is that $r^2_{session}$ of the relation $VO_2 = f(V_E)$ is significantly higher than the $r^2_{session}$ of the relation $VO_2 = f(HR)$ for groups 1, 2, 3 and 4 (Table 2). Moreover, this result is observed during exercise with oxygen consumption steady state (walking with or without load during 3 or 6 min), and during exercise without oxygen consumption steady state (walking with or without load during 1 min or intermittent work). Another interesting result is observed when the sets of measures of the sessions carried-out by each subject are joined together (walking with and without loads, intermittent work). For 10 of the 12 subjects, the coefficient of determination $r^2_{subject}$ of the relation $VO_2 = f(V_E)$ is higher than the $r^2_{subject}$ of the relation $VO_2 = f(HR)$ (Table 3). Moreover, the mean coefficient of the relation $VO_2 = f(V_E)$ is significantly higher than the mean coefficient of the relation $VO_2 = f\,(HR)$.

The differences among $r^2_{session}$ and $r^2_{subjects}$ from the relations $VO_2 = f\,(V_E)$ and $VO_2 = f\,(HR)$ may be explained by the different mechanisms of control of V_E and HR (Strange et al., 1993; Whipp and Ward, 1982). To date, no study has been able to predict, on a strictly physiological level, the preferential interest in using HR compared with V_E to estimate VO_2.

Nevertheless, many arguments previously mentioned imply that V_E seems to be a parameter much better correlated with VO_2 than HR, in particular during physical activities of different intensities. Hence, it is legitimate to think that a relation between V_E and VO_2 could be established to estimate EE starting only from the measurement of V_E. It is interesting to develop a new device to measure the V_E of a subject in a non-invasive way. This innovation would make it possible to measure V_E in daily life conditions (light to moderate intensities). It is currently possible to precisely measure V_T, T_I, and T_E and to calculate V_E, thanks to a non-invasive device using magnetometry (McCool et al., 2002). We currently develop a light and portable device allowing the direct measurement of V_E based on the coupling of four magnetometers. This device has no invasive character and could quickly be used to estimate EE under free-living conditions. Furthermore, new portable devices (Actiheart and SensorWear Armband) demonstrate the added value of combining several parameters, and represent certainly the future solutions to estimate EE in free living condition. From this model, it would be possible to couple HR to another physiological parameter to overcome the difficulties of the HR method to estimate EE during low levels of activity. So, V_E would estimate EE during light and moderate activity, and HR would be a complementary parameter to improve the estimation of EE during moderate activity requesting important muscular masses. It would be necessary to integrate this system into clothing (shirt or vest) to make it possible to process measurements under daily life circumstances.

Conclusion

This study shows that V_E is more strongly correlated with VO_2 than HR during physical activities of different intensities. This result confirms the interest to looking for V_E to estimate EE.

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Key points

- Ventilation is more strongly correlated with oxygen uptake than heart rate during physical activities of different intensities.
- This study shows the interest to looking for ventilation to estimate energy expenditure.
- This study is a promising approach to develop a new method to estimate energy expenditure
- An interesting perspective could be to develop a light and portable device to measure ventilation based on the coupling of four magnetometers.

AUTHORS BIOGRAPHY

Steven GASTIINGER
Employment
PhD Student at the Department of Sport Sciences, Rennes 2 University, France
Degree
MSc
Research interests
Quantification of physical activities, estimation of energy expenditure, development of a new portable device to measure ventilation.
E-mail: gastingersteven@yahoo.fr
steven.gastinger@univ-rennes2.fr

Anthony SOREL
Employment
PhD Student at the Department of Sport Sciences, Rennes 2 University, France
Degree
MSc
Research interests
Biomechanics, quantification of physical activities, motion analysis, motion recognition, virtual reality.
E-mail: anthony.sorel@univ-rennes2.fr

Guillaume NICOLAS
Employment
Lecturer at the Department of Sport Sciences, Rennes 2 University, France
Degree
MSc, PhD
Research interests
Biomechanics, motion analysis / simulation, quantification of physical activity, bipedal locomotion, swimming.
E-mail: guillaume.nicolas@univ-rennes2.fr

Arlette GRATAS-DELAMARCHE
Employment
Professor at the Department of Sport Sciences, Rennes 2 University, France
Degree
PhD and authorize to supervise research
Research interests
Oxidative stress, metabolic diseases, beneficial effect of physical activity on health.
E-mail: arlette.delamarche@univ-rennes2.fr

Jacques PRIOUX
Employment
Professor at the ENS Cachan, Antenne de Bretagne, France
Degree
PhD and authorize to supervise research
Research interests
Quantification of physical activities, estimation of energy expenditure, ventilatory response to exercise, training and intermittent work
E-mail: jacques.prioux@bretagne.ens-cachan.fr

✉ **Steven Gastinger**
M2S Laboratory (Movement, Health and Sports Science): Physiology and Biomechanics, UFR APS, Rennes 2 University, Avenue Charles Tillon – CS 24414 – 35044 Rennes Cedex, France