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Estimation of Metabolic Energy Expenditure during Short Walking Bouts

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ABSTRACT

Assessment of metabolic energy expenditure from indirect calorimetry is currently limited to sustained (>4 min) cyclic activities, because of steady-state requirements. This is problematic for patient populations who are unable to perform such sustained activities. Therefore, this study explores validity and reliability of a method estimating metabolic energy expenditure based on oxygen consumption ($\dot{V}O_2$) during short walking bouts. Twelve able-bodied adults twice performed six treadmill walking trials (1, 2 and 6 min at 4 and 5 km/h), while $\dot{V}O_2$ was measured. Total $\dot{V}O_2$ was calculated by integrating net $\dot{V}O_2$ over walking and recovery. Concurrent validity with steady-state $\dot{V}O_2$was assessed with Pearson's correlations. Test-retest reliability was assessed using intra-class correlation coefficients (ICC) and Bland-Altman analyses. Total $\dot{V}O_2$ was strongly correlated with steady-state $\dot{V}O_2$ ($r = 0.91–0.99$), but consistently higher. Test-retest reliability of total $\dot{V}O_2$ ($ICC = 0.65–0.92$) was lower than or comparable to steady-state $\dot{V}O_2$ ($ICC = 0.83–0.92$), with lower reliability for shorter trials. Total $\dot{V}O_2$ discriminated between gait speeds. Total oxygen uptake provides a useful measure to estimate metabolic load of short activities from oxygen consumption. Although estimates are less reliable than steady-state measurements, they can provide insight in the yet unknown metabolic demands of daily activities for patient populations unable to perform sustained activities.

Introduction

Assessment of metabolic energy expenditure during daily life activities is important because it can specify the physiological demands of independent living. A compendium of the energy expenditure for various daily activities for able-bodied people exists, and is widely used in physiotherapy and occupational therapy [1]. While energy demands of activities can be significantly different for people with disabilities or chronic conditions [2, 3], a similar compendium does not exist for these groups. Understanding physiological demands of daily life for people with disabilities can help improve rehabilitation interventions and set individual training goals. Unfortunately, due to methodological limitations, the most functionally-limited people are often excluded from energy expenditure analysis.

Metabolic energy expenditure is most often estimated from oxygen consumption ($\dot{V}O_2$), measured via breath-by-breath gas exchange measurements. After the start of submaximal cyclic exercise, $\dot{V}O_2$ rises exponentially towards a steady state in 1–3 min [4]. To obtain a reliable approximation of metabolic energy expenditure, at least 2 min of steady-state activity $\dot{V}O_2$ are averaged. This procedure limits analysis of metabolic energy expenditure to relatively long-lasting (> 4 min), cyclic activities. For many patients or deconditioned individuals, such exercise durations are not feasible. Unfortunately, there is currently no validated method to estimate metabolic energy expenditure from $\dot{V}O_2$ during shorter bouts of activity (< 4 min).

Estimating steady-state oxygen consumption from the $\dot{V}O_2$ during the first minutes of exercise of short, non-steady-state tasks is difficult, if not impossible: Both the time constant of the exponential rise to steady-state $\dot{V}O_2$, as well as steady-state $\dot{V}O_2$ itself, differ greatly from person to person, and between exercise intensities [4]. Studies that did estimate metabolic energy expenditure from $\dot{V}O_2$ during short activities have used different approximations. For example, Castro et al. [5] reported the $\dot{V}O_2$ at the end of the activity, whereas Novak and Brouwer [6] reported both average $\dot{V}O_2$ and peak $\dot{V}O_2$ during stair ambulation. The validity and reliability of these methods, however, are questionable. The $\dot{V}O_2$ signal is variable in nature and, consequently, an average over a significant number of breaths is needed to obtain a reliable estimate of overall oxygen consumption. Peak values or values at the end of exercise are prone to measurement errors, since only a limited number of breaths are analysed. On the other hand, averaging $\dot{V}O_2$ over the whole task duration ignores metabolic energy expenditure from the anaerobic pathways at the beginning of the task, which is not represented in the $\dot{V}O_2$ signal.

A possible solution to this problem is to include excess post-exercise oxygen consumption (EPOC) in the assessment. After a bout of submaximal exercise, $\dot{V}O_2$ gradually drops to resting metabolic rates within 10 minutes [7, 8]. The oxygen consumption after exercise above resting $\dot{V}O_2$ – the EPOC- is thought to reflect the replenishment of oxygen stores in the muscle, ATP and CP resynthesis, lactate removal, and to a lesser degree the maintenance of increased temperature, circulation and ventilation [9]. Thus, EPOC can largely be attributed to the metabolic energy expenditure during the activity.

The oxygen uptake kinetics and EPOC of short bouts of cycling and treadmill walking have been described in a number of studies that investigated the efficiency of aerobic versus anaerobic work [7, 10, 11]. In these studies, EPOC was added to the $\dot{V}O_2$ during exercise to quantify 'total oxygen cost' of the task, this total oxygen cost was then compared to steady-state $\dot{V}O_2$ at similar workloads. Whipp et al. [7] let three male athletes cycle at submaximal intensity for time periods of one to six minutes. For these three participants, total oxygen cost and oxygen cost derived from steady-state measurements of the trials that were three minutes or longer were closely correlated. However, a larger total oxygen cost was found for the 1- and 2-min trials, compared to that derived from the longer steady-state activity [7]. In a larger study with 14 participants, Katch et al. [10] found that total oxygen cost in both short and long (one to seven min) trials was higher than steady-state requirements. McMiken et al. [11] found similar results and showed that, on average, EPOC in trials ranging from 0.5–20 min was 1.5 times higher than oxygen deficit predicted by steady-state measurements. However, this study was limited by the fact that each trial duration was performed by a different participant. Therefore inter-individual differences may have influenced the results. The results of these studies indicate that EPOC is higher than the oxygen deficit at the beginning of the exercise and hence the 'total oxygen cost' of short trials would be higher than oxygen demand predicted from steady-state activity.

None of the abovementioned studies, however, have evaluated the test-retest reliability of total oxygen cost, nor did they investigate whether observed differences were affected by exercise intensities. Although numerous studies have investigated EPOC and oxygen uptake kinetics of longer bouts of exercise [9], to the authors knowledge no previous studies have studied the validity and reliability of the oxygen uptake kinetics and EPOC of short, non-steady-state, submaximal exercise. Therefore, the current study evaluated the validity and reliability of estimating metabolic energy expenditure from oxygen consumption of short treadmill walking trials in healthy adults. Metabolic energy expenditure was estimated by the total oxygen uptake method, in which EPOC was added to the time integral of oxygen consumption during walking. Validity of this method was tested in two ways: first by comparing it to steady-state $\dot{V}O_2$, and second by assessing whether it could discriminate between two different gait speeds. Additionally, test-retest reliability was assessed by repeating the protocol on a second day. This study is a first step in developing a method to estimate metabolic energy expenditure in people unable to sustain longer periods of exercise.

We hypothesized that total oxygen uptake would strongly correlate to steady-state oxygen consumption at similar intensities and that the potential overestimation of oxygen consumption would be higher for the shorter trials. Furthermore, we expected that both the total oxygen uptake method and the steady-state method could differentiate between exercise intensities with similar sensitivity. Reliability of all measures was expected to be good, with better reliability for the longer trials, due to the larger influence of variability in the $\dot{V}O_2$ signal in the short trials.

Materials and Methods

Participants

A convenience sample of twelve healthy adults (age 25.9 ± 3.6 years, BMI 24.2 ± 4.7 kg/m^2, 6 male / 6 female) participated in this study. Participants were recruited via flyers, e-mail and word of mouth. Exclusion criteria were: (1) exercising more than 3 hours/week, (2) coronary artery disease, (3) use of a walking aid, (4) musculoskeletal or neurological abnormalities influencing walking, or (5) cardiorespiratory conditions influencing oxygen consumption. The local ethics committee of the Faculty of Behavioral and Movement Sciences of the 'Vrije Universiteit Amsterdam' approved this study. This study was conducted according to international ethical standards [12]. All participants were fully informed about the aim and protocol of the study and signed a written informed consent before participation.

Procedures

Participants were tested on two days, separated by a minimum of 24 hours and a maximum of two weeks. The measurements took place at similar times of the day, and measurement protocol was identical on both days.

Participants were asked to refrain from exercising at least 24 hours before the measurements and to refrain from taking food and caffeinated beverages for at least two hours before the measurements. Before testing, participants' height and weight were measured.

Each measurement day started with a 10-minute resting metabolic rate measurement, while the participant was sitting in a chair. Subsequently, six treadmill walking trials of different speed (4 and 5 km/h) and duration (1, 2 and 6 min) were performed in random order. The treadmill was set at a zero degree inclination. The speeds were chosen such that participants in this healthy, young population exercised at a low intensity. Each trial started with the participant standing on the treadmill for one minute and ended with the participant sitting in a chair for 10 minutes. This ten-minute duration was considered sufficient to return to resting values after submaximal exercise [7, 8], therefore no breaks were imposed between trials, unless the participant requested a break from the mask.

During all trials, breath-by-breath gas exchange measurements were performed (Quark CPET, Cosmed, Rome, Italy). Before each session, the instrumentation was calibrated following the manufacturer's instructions.

Data analysis

Resting oxygen consumption was determined based on the $\dot{V}O_2$ during the seated period after each separate trial. An exponential model following equation 1 was fitted to the oxygen consumption during the 10-minute recovery period.

$$\dot{V}O_{2(t)} = a * e^{-(b*t)} + c \qquad 1$$

In this equation, $\dot{V}O_2$ represents oxygen consumption in mL/min and *t* is time from end of walking till end of measurement. The constants a, b and c were fitted using a least-squares model. R^2-values of the resulting models ranged from 0.55 to 0.99. The constant *c* in this the model (i. e. the horizontal asymptote of the curve) was considered the resting $\dot{V}O_2$ for the designated measurement. Resting $\dot{V}O_2$ was then subtracted from the $\dot{V}O_2$ data to obtain net $\dot{V}O_2$ ($\dot{V}O_2$net).

To determine the end of EPOC, the $\dot{V}O_2$ signal was low-pass filtered with a five-breaths average to reduce the influence of breath-by-breath variability. The first timepoint at which this five-breaths average came within five percent of the resting $\dot{V}O_2$ was considered the end of EPOC. This analysis is depicted in ▶ **Fig. 1**.

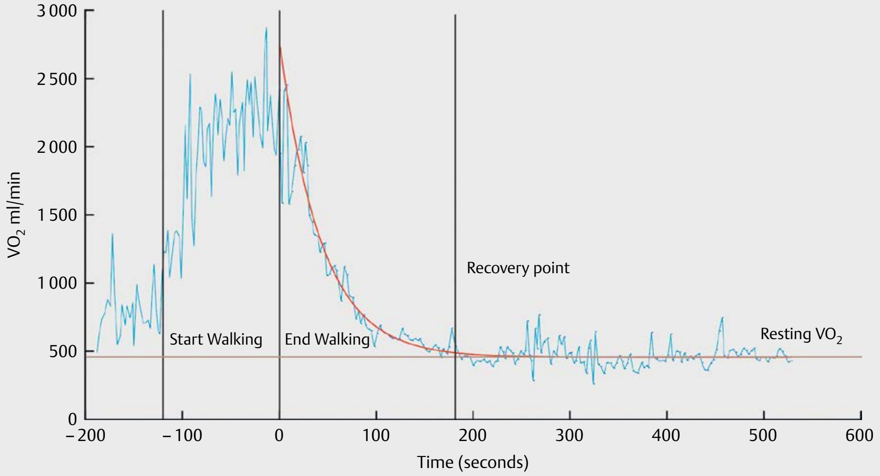
The total oxygen uptake method was performed as follows: Total oxygen uptake of a walking trial was calculated by integrating $\dot{V}O_2$net from start of walking till end of EPOC. Total oxygen uptake was then divided by walking duration to obtain the avarage rate of oxygen consumption for walking: $\dot{V}O_2$tot (▶ **Fig. 2**).

For the 6-min walking trials, next to $\dot{V}O_2$tot, steady-state $\dot{V}O_2$ ($\dot{V}O_2$ss) was determined by averaging $\dot{V}O_2$net over the last two minutes of walking (▶ **Fig. 2**). The existence of a steady-state $\dot{V}O_2$ in the 6-min trials was checked visually both online and offline.

Absolute values of EPOC were determined for each trial as a secondary outcome measure for interpretation of results. Additionally, oxygen deficit was calculated for each trial, representing the oxygen that would have been required for aerobic metabolism during the first part of the trial. This was calculated under the assumption that $\dot{V}O_2$ss is constant at each separate exercise intensity for each bout duration. First, oxygen demand during walking was estimated by multiplying $\dot{V}O_2$ss by walking time. Oxygen deficit was then defined as the difference between this estimated oxygen demand and measured oxygen consumption during walking.

Statistical analysis

Data were analysed with SPSS (IBM SPSS Statistics version 25.0, IBM Corp.). Data were checked for normality using visual inspection,



▶ **Fig. 1** Example of the exponential fit to determine resting $\dot{V}O_2$ and end of excess post-exercise oxygen consumption (EPOC). The black vertical lines depict the start of walking, end of walking and the recovery point respectively. The red line depicts the exponential fit on the data after exercise. The grey horizontal line depicts the resting $\dot{V}O_2$ derived from this fit. The recovery point (i. e. end of EPOC) is the first point where a five-breaths-average was within a 5 % range of resting $\dot{V}O_2$.

skewness and kurtosis inspection and the Kolmogorov-Smirnov and Shapiro-Wilk tests. When the assumption of normality was violated, non-parametric equivalents of statistical tests were used. Mean (± SD) scores were computed for all trials.

One participant's 6-min trial at 4 km/h was not taken into account, since a steady-state $\dot{V}O_2$ was not confirmed for this trial. All other trials were included in the analysis.

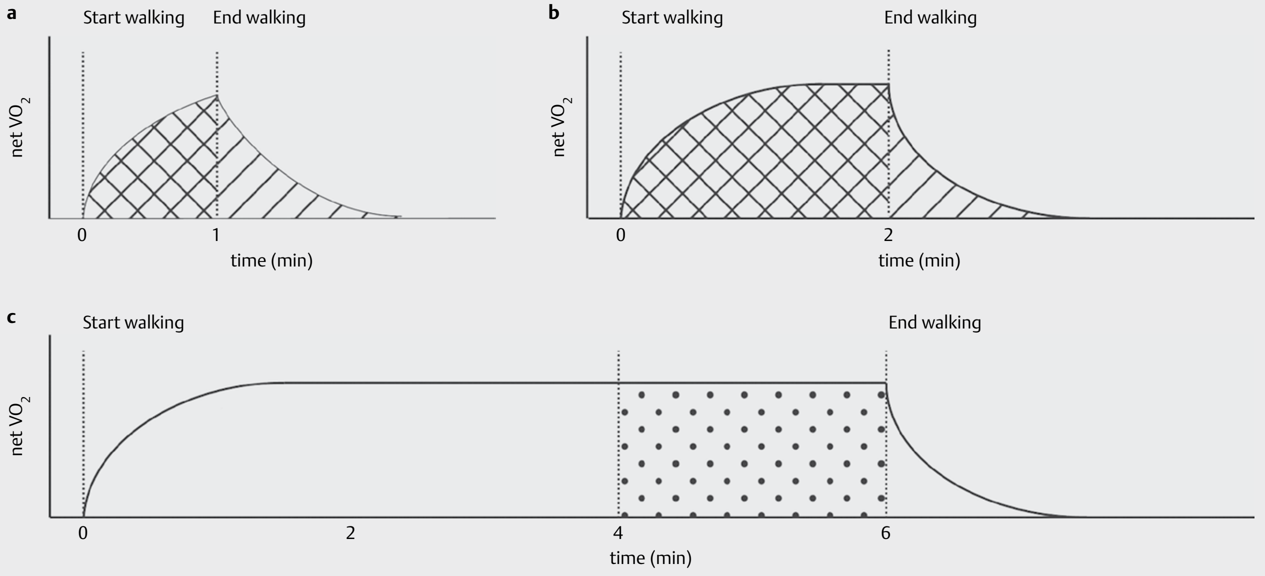
Test-retest reliability of both $\dot{V}O_2$ss and $\dot{V}O_2$tot were evaluated with intra-class correlation coefficients (ICC) with a 2-way mixed, absolute agreement model [13]. Corresponding confidence intervals were calculated. Reliability was considered poor, moderate, good or excellent when ICC was < 0.50, ≥ 0.50 and < 0.75, ≥ 0.75 and < 0.90 or ≥ 0.90 respectively [13]. Bland-Altman analyses were used to determine bias and limits of agreement (LOA) [14].

The results of two trials with similar speed and similar duration were averaged for the validity analyses. Correlations between $\dot{V}O_2$tot (1-, 2- and 6-min) and $\dot{V}O_2$ss were assessed using Spearman's correlation analyses. A factorial, repeated-measures analysis of variance (ANOVA) was conducted to assess the effect of gait speed (4 and 5 km/h) and assessment type (1-min $\dot{V}O_2$tot, 2-min $\dot{V}O_2$tot, 6-min $\dot{V}O_2$tot, $\dot{V}O_2$ss) on oxygen consumption. Significant effects were followed up by post-hoc paired-sample t-test using Bonferroni corrections. A p-value of < 0.05 was considered significant.

Results

Reliability

ICC's of $\dot{V}O_2$tot were good or excellent, with the exception of the 4 km/h, 2-min trial, which was moderate (▶ **Table 1**). No significant bias was found between repetitions, except for the 1-min $\dot{V}O_2$tot at 5 km/h. The ICC's of $\dot{V}O_2$ss were also good or excellent and no significant bias was found. LOA were larger for the 1- and 2-min

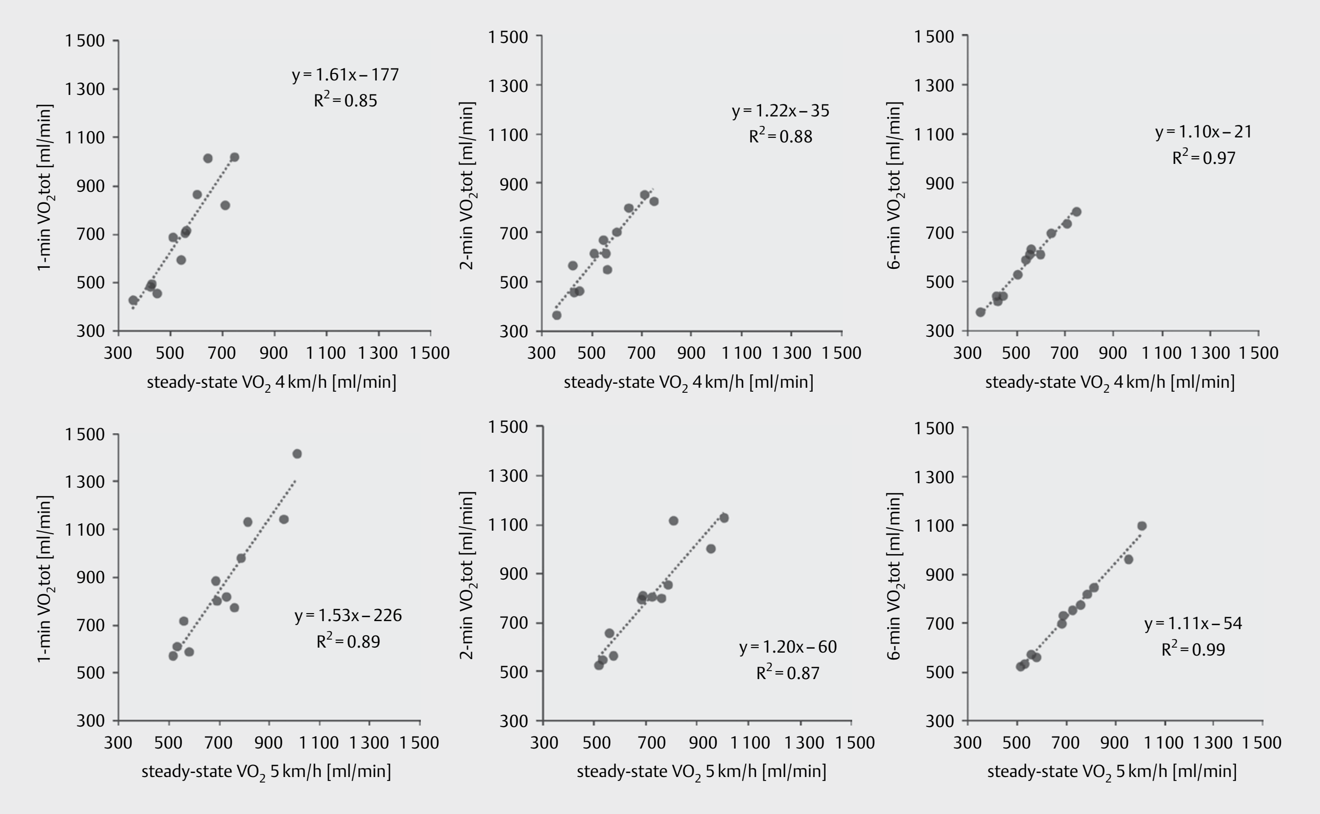


▶ **Fig. 2** Schematic representation of the determination of $\dot{V}O_2$tot for the 1-min and 2-min trial (2a and 2b respectively) and $\dot{V}O_2$ss (2c). $\dot{V}O_2$ss was estimated from the last two minutes of walking in the 6-min trials (dotted surface). $\dot{V}O_2$tot was estimated by adding excess post-exercise oxygen consumption (EPOC; diagonal stripes) to the oxygen consumption during walking ($\dot{V}O_2$walk, double striped surface). Note: $\dot{V}O_2$tot was also determined for the 6-min trial but is not indicated in this figure.

▶ **Table 1** Reliability measures.

Speed	**4 km/h**				**5 km/h**			
Type	**$\dot{V}O_2$tot 1 min**	**$\dot{V}O_2$tot 2 min**	**$\dot{V}O_2$ss min**	**$\dot{V}O_2$ss**	**$\dot{V}O_2$tot 1 min**	**$\dot{V}O_2$tot 2 min**	**$\dot{V}O_2$tot 6 min**	**$\dot{V}O_2$ss**
ICC (CI)	0.82 (0.50–0.95)	0.65 (0.16–0.88)	0.86 (0.57–0.96)	0.83 (0.52–0.95)	0.89 (0.61–0.97)	0.88 (0.65–0.96)	0.96 (0.86–0.99)	0.92 (0.75–0.98)
BIAS (ml/min)	2.1	–35	–34	–29	–69 *	–19	–14	–29
LOA (ml/min)	300	280	140	140	210	210	110	120

ICC: Intraclass Correlation Coefficients; CI: 95 % Confidence Interval; BIAS: bias from Bland-Altman analysis; LOA: Limits Of Agreement from Bland-Altman analysis. * significantly different from zero at $p < 0.05$ level.



▶ **Fig. 3** Correlations between $\dot{V}O_2ss$ and $\dot{V}O_2tot$ for 4 km/h (upper panels) and 5 km/h (lower panels). Correlation equations and r^2 values are depicted next to the figures.

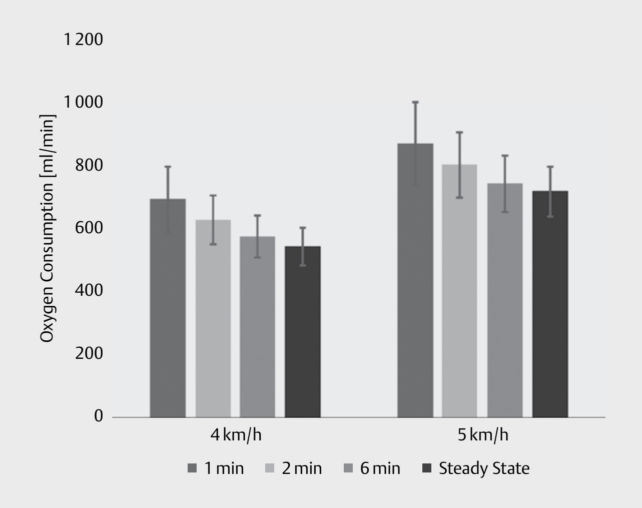
$\dot{V}O_2tot$, compared to the 6-min $\dot{V}O_2tot$. However, LOA were similar between 6-min $\dot{V}O_2tot$ and $\dot{V}O_2ss$.

Validity

$\dot{V}O_2ss$ was strongly correlated with $\dot{V}O_2tot$ for all trial durations and speeds with correlation coefficients ranging from 0.91 to 0.99 (▶ **Fig. 3**).

The ANOVA revealed a main effect on oxygen consumption for both assessment type (F(1.50,11) = 20.17) and gait speed F(1,11) = 108.92) (▶ **Fig. 4**). No significant interaction effect was found (F(1.57,11) = 0.11), indicating that speed did not influence the relationship between assessment types. Post-hoc analyses showed that oxygen consumption at 5 km/h was significantly higher than at 4 km/h for all assessments. Furthermore, $\dot{V}O_2ss$ was consistently lower than all $\dot{V}O_2tot$ assessments and 6-min $\dot{V}O_2tot$ was lower than 1- and 2-min $\dot{V}O_2tot$. No significant difference was found between the 1- and 2-min $\dot{V}O_2tot$.

Although total oxygen uptake during walking increased with increasing walking time, EPOC and oxygen deficit values were not significantly different between trials of different duration at the same speed (▶ **Table 2**). Estimated oxygen deficit was smaller than EPOC for all trials.



▶ **Fig. 4** Oxygen consumption estimated from 1, 2 and 6 min via the total oxygen uptake method ($\dot{V}O_2tot$) and via the steady-state method ($\dot{V}O_2ss$), for both the 4 and 5 km/h trials. All trials were significantly different from each other, except for the 1- and 2-min $\dot{V}O_2tot$ at similar intensities.

Discussion

We evaluated the validity and reliability of estimating metabolic

▶**Table 2** Mean values of oxygen consumption ($\dot{V}O_2$), oxygen demand during walking (VO_2walk), excess post-exercise oxygen consumption (EPOC), total oxygen uptake and estimated oxygen deficit.

Speed	**4 km/h**				**5 km/h**			
Assessment	**$\dot{V}O_2$tot 1 min**	**$\dot{V}O_2$tot 2 min**	**$\dot{V}O_2$tot 6 min**	**$\dot{V}O_2$ss**	**$\dot{V}O_2$tot 1 min**	**$\dot{V}O_2$tot 2 min**	**$\dot{V}O_2$tot 6 min**	**$\dot{V}O_2$ss**
$\dot{V}O_2$tot (ml/min)	692 (208)	626 (155)	573 (133)	541 (119)	868 (258)	801 (206)	741 (178)	716 (159)
$\dot{V}O_2$ walk (ml)	373 (97)	906 (219)	3086 (690)		461 (118)	1167 (267)	3984 (812)	
EPOC (ml)	371 (158)	388 (140)	398 (146)		463 (177)	501 (188)	509 (186)	
Total $\dot{V}O_2$ (ml)	744 (226)	1294 (326)	3485 (812)		924 (279)	1668 (425)	4493 (1086)	
Oxygen Deficit (ml)	203 (63)	200 (69)	201 (97)		300 (77)	324 (87)	359 (73)	

Values are presented as mean (SD). Note that assessment time was not always exactly 1, 2 or 6 min based on the variability of the breath-by-breath data.

energy expenditure from the total oxygen uptake during walking and recovery in short treadmill walking trials. Total oxygen consumption of walking was obtained by adding EPOC to the oxygen consumption during walking. This total oxygen uptake was then divided by walking time to obtain an estimate of the average rate of oxygen consumption: $\dot{V}O_2$tot. $\dot{V}O_2$tot was compared to conventional steady-state $\dot{V}O_2$. The underlying goal was to develop a method that could estimate metabolic energy expenditure of daily life activities for patients who are unable to perform activities long enough to reach a steady state of oxygen consumption.

Reliability

Both $\dot{V}O_2$tot and $\dot{V}O_2$ss showed good to excellent test-retest reliability based on ICCs, except for the 2-min, 4 km/h $\dot{V}O_2$tot, which was moderately reliable, also indicated by the large confidence interval. In addition, Bland-Altman LOA of the 6-min $\dot{V}O_2$tot were comparable to those of $\dot{V}O_2$ss; however, LOA were almost two times larger for the 1- and 2-min $\dot{V}O_2$tot. The smaller number of breaths available in these short trials likely caused the larger variability between measuremts. The large LOA indicate that a difference in oxygen consumption for an individual can only be reliably detected if it is larger than approximately 300 ml O_2/min [14]. This difference of around 1 MET is quite large, since training effects below this level can already be relevant, especially in patients with low fitness levels. However, based on ICC values, the $\dot{V}O_2$tot method can be used to assess differences in oxygen consumption between activities or within a group. Furthermore, the test-retest reliability of the steady-state measurements was not higher than that of the 6-min $\dot{V}O_2$tot. It seems that the longer the measurements, the better the test-retest reliability, independent of the method used for analysis.

Validity

In line with our hypothesis, both $\dot{V}O_2$tot and $\dot{V}O_2$ss could distinguish gait speeds of 4 and 5 km/h, reflecting sensitivity to differences in exercise intensity. The differences between intensities depended neither on the type of assessment, nor on trial length, as shown by the lack of interaction effect. This indicates that both steady state and the total oxygen uptake method can be used to compare the metabolic load between different activities.

As hypothesized, $\dot{V}O_2$tot was strongly correlated to $\dot{V}O_2$ss, and it was systematically higher than $\dot{V}O_2$ss. This systematic difference decreased with longer trial durations: The 1-min $\dot{V}O_2$tot was on average 1.5 times larger than $\dot{V}O_2$ss, whereas the 6-min $\dot{V}O_2$tot was only 1.05 to 1.1 times larger, thus approximating $\dot{V}O_2$ss. This can be explained by the fact that EPOC was higher than oxygen deficit, and did not differ between trial durations at similar intensities. The lack of this difference led to a larger deviation from steady-state measurements in short trials, which is in line with previous studies [7, 10, 11]. However, this study is the first to confirm this finding consistently in a repeated measures design and at different intensities.

Since metabolic energy expenditure was estimated indirectly from oxygen uptake in this study, it is unclear whether the difference between $\dot{V}O_2$tot and $\dot{V}O_2$ss can be attributed to a real difference in the metabolic requirement for short walking bouts versus steady-state walking, or to the fact that not all oxygen uptake in EPOC represents metabolic work during walking. Whipp et al. [7] used an active baseline (i. e. cycling at 0 Watts) to eliminate effects of starting and stopping, but they still found that total oxygen uptake for 1- and 2-min trials was higher than predicted from steady-state requirements. They hypothesised that in the longer trials lactate released from the anaerobic pathway at the start of exercise might be used as a substrate during the remainder of the trial. Whereas in the shorter trials it is stored via a different pathway, in which the oxygen consumed does not contribute to metabolic energy production, but it is still represented in EPOC. However, EPOC in the current study did not differ between trial durations at similar intensities. Therefore, our data do not support this hypothesis. Hence, we cannot conclude whether the overestimation of oxygen consumption is due to muscle work for starting and stopping of walking, or to metabolic processes beyond muscle work for task execution.

If the overestimation of oxygen deficit from EPOC were constant, a correction factor of EPOC could lead to predictions of $\dot{V}O_2$ss from $\dot{V}O_2$tot. Some authors have indeed used this approach to estimate anaerobic energy production in exercises at different intensities [15]. However, we found a large inter- and intra-individual variability of the overestimation of oxygen deficit from EPOC: EPOC was on average 2.3 (± 2.6) times and 1.9 (± 1.5) times higher for the 4 km/h trials and 5 km/h trials, respectively. Since no consistent pattern of overestimation of oxygen deficit can be derived from our study, we advise against using a correction factor to estimate oxygen deficit from EPOC for individual participants. However, since we showed a strong correlation between $\dot{V}O_2$tot and $\dot{V}O_2$ss, on group level a correction factor on $\dot{V}O_2$tot could be used to predict $\dot{V}O_2$ss. When using this correction factor, the potentially higher metabolic load of the short tasks is omitted and the assumption is made that the subject can reach a steady state. Consequently, estimating $\dot{V}O_2$ss from $\dot{V}O_2$tot should be done with caution.

Limitations and recommendations

Although the steady-state $\dot{V}O_2$ method remains the gold standard to estimate metabolic energy expenditure, the total oxygen uptake method might provide an alternative for people unable to reach steady-state $\dot{V}O_2$. There are, however, some limitations to this method that need to be considered. First, $\dot{V}O_2$tot is systematically higher than $\dot{V}O_2$ss at similar intensities, and it is unclear whether this overestimation represents extra metabolic energy for mechanical work. Since the overestimation is not consistent among individuals, it cannot be adjusted for on an individual level. Although it could be corrected for at group level when taking exercise duration into account. Second, assessment of $\dot{V}O_2$tot assumes that workload of the activity is of moderate intensity, while this intensity cannot be assessed by confirming a steady state. Monitoring the respiratory quotient ($RQ < 1.0$) or the rating of perceived exertion during the short activity might be ways to control for exercise intensity. Third, the reliability of the assessment depends on bout duration: a longer measurement time is preferred when this is possible for the patient. Alternatively, repeating measurements and averaging results over multiple short bouts might be used to increase reliability. Last, it should be stressed that both steady-state $\dot{V}O_2$ and $\dot{V}O_2$tot do not take into account the metabolite used at muscular level. For steady-state conditions, the substrate use and actual metabolic energy derived from the oxidation could be derived from RQ, but this cannot be done for our $\dot{V}O_2$tot assessment. However, in most clinical studies this final conversion from steady-state oxygen consumption to metabolic power is not performed, accepting a small incongruence between both measures.

The total oxygen uptake method might be used to assess differences or relative differences in metabolic energy expenditure between patient groups and able-bodied people. Furthermore, it can give insight into the differences in energy expenditure between activities of similar duration. Lastly, it might be used on a group level to assess the effects of training interventions or assistive technology targeting movement economy. To assess energy expenditure on an individual level, the above mentioned methods should be considered to increase reliability.

In this study we included able-bodied participants to be able to compare the total oxygen uptake method with steady-state measurements. Future studies should assess the reliability of this method within the targeted patient populations and in different exercise modalities.

Conclusion

The presented total oxygen uptake method is a practical method to estimate metabolic energy expenditure that does not require sustained activity to be performed. Given that test-retest reliability is moderate to excellent and that correlations with steady-state oxygen consumption are high, the method might provide a useful tool for those unable to perform activities long enough to attain a steady-state energy expenditure. Thus, despite its limitations, the total oxygen uptake method might provide the only way to estimate metabolic energy expenditure from oxygen consumption in the most functionally-limited people.

Conflict of Interest

The authors declare that they have no conflict of interest.

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