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Reliability of the VmaxST portable metabolic measurement system

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Abstract

The purpose of this study was to evaluate the reliability of the VmaxST portable metabolic measurement system. Forty-five healthy adults (age = 25.7 ± 5.9 yr; height = 171.8 ± 9.1 cm; weight = 69.6 ± 12.8 kg; $\text{VO}_{2\text{peak}}$ = 40.7 ml/kg/min; percent fat = 21.7 ± 11.0) performed two separate and identical exercise routines on different days consisting of treadmill walking at 2.0 mph (53.6 m/min), 3.0 mph (80.5 m/min), and 4.0 mph (107.3 m/min) and running at 6.0 mph (160.9 m/min). V_E and gas exchange were measured continuously breath-to-breath. A random effects model on log-transformed data yielded coefficients of variation (CV) and intraclass correlation coefficients (ICC) for VO_2 and V_E of 5.2–7.6%, and 0.77–0.92, respectively, for all walking and running trials. For VCO_2 , CVs were higher (10–12%) and ICCs lower (0.70–0.81). Ordinary least squares regression between the individual difference scores and the individual mean scores for V_E , VO_2 and VCO_2 , respectively, indicated no systematic bias (all $p > 0.05$). Bland-Altman analysis also illustrated no systematic bias between repeated measurements. The VmaxST provides reliable measurements of VO_2 and V_E during walking and running eliciting V_E and VO_2 at least up to ~56 and 2.2 l/min, respectively. The system appears to be less reliable for measuring VCO_2 .

INTRODUCTION

A number of portable metabolic measurement systems have been developed during the past 10–15 years. These systems have been evaluated in a number studies, with most of the emphasis on validity [2,4–6,8,11,12,14–18,23,24,26,27,29]. Much less is known about the reliability of these systems [2,6,12]. Reliability studies have generally used relatively small sample sizes, typically less than 25 [2], with one study using only one subject [17]. Sample size is important for the precision of error estimates, and it has been suggested that a minimum of 40 subjects be used in validity/reliability studies of metabolic measurement systems [2].

The VmaxST has been previously assessed for accuracy [4,27]. One study reported that the VmaxST underestimated ventilation (V_E) and oxygen uptake [VO_2] when compared to a gas exchange simulator and during incremental treadmill exercise when compared to the Douglas Bag (DB) method [27], and another study reported that the VmaxST provided measurements of V_E and VO_2 that were not significantly different from those obtained with the DB method during rest and 5 min of constant-load cycle ergometry [4]. However, the reliability of the VmaxST has not been established. Furthermore, previous validation studies with the VmaxST have used relatively few subjects (10 to 11) [4,27].

Therefore, we chose to assess the reliability of the VmaxST during treadmill walking and running. As suggested by Atkinson et al. [2] we recruited >40 subjects, including men and women, to perform two treadmill walking and running routines in order to assess the reliability of the VmaxST portable metabolic measurement system.

METHODS

Subjects

Twenty-six women and 19 men between the ages of 19 and 40 participated in this study (Table 1). Subjects were generally physically active, and none was a competitive runner or race walker. Written informed consent was obtained from each subject, and the University of Virginia's Institutional Review Board approved the study. A pre-participation medical history and physical examination was completed on each subject to ensure good health.

Experimental Design

Each subject reported to the exercise physiology laboratory on three occasions, with 2–7 days between sessions. . On one occasion body fat percentage was determined by air displacement plethysmography [7] and an incremental treadmill walking protocol was administered to assess peak aerobic capacity. These measurements were performed for purposes of subject characterization. On each of the two other occasions a routine involving walking and running was performed. These two routines were identical in nature and for a given subject were performed at the same time of day on each occasion. Subjects were instructed to come to the laboratory at least two hours post-absorptive, to not perform any exercise prior to the session on the day of the test, and to not engage in strenuous/exhaustive exercise on the day before the test. No attempt was made to control macronutrient composition of the diet on the day of or before each test.

Incremental treadmill walking protocol

A modified Balke protocol was performed on a motorized treadmill. Subjects began walking at 3.3 mph (88.5 m/min), 0% grade for the first min. Grade was then increased to 2% for one min, and then increased by 1% every subsequent min. If a 25% grade was reached, velocity was increased by 0.5 mph (13.4 m/min) every min. The test was terminated at the point of volitional exhaustion. Time to exhaustion averaged 24.5 ± 4.1 min. At exhaustion heart rate averaged 187 ± 11 beats per min and respiratory exchange ratio averaged 1.14 ± 0.09 .

Exercise routines for assessment of reliability of VmaxST

Upon arriving at the laboratory subjects were fitted with the VmaxST portable metabolic measurement system (VIASYS, Yorba Linda, CA) and rested (sitting) for five min while seated metabolic rate was obtained. Subjects then walked on a motor-driven treadmill at 2.0 (53.6 m/min), 3.0 (80.5 m/min), and 4.0 mph (107.3 m/min), and ran at 6.0 mph (160.9 m/min). Subjects exercised for 5 min at each speed, with 3 min of rest (standing) in between each exercise period.

Determination of $\dot{V}_E$, $\dot{V}O_2$, and $\dot{V}CO_2$

During all three exercise sessions $\dot{V}_E$ and pulmonary gas exchange were measured breath-by-breath with the VmaxST portable metabolic measurement system. For the incremental treadmill exercise test $\dot{V}O_2$ was averaged over 30-s intervals and the highest 30-s average $\dot{V}O_2$ achieved was taken as the $\dot{V}O_{2peak}$. For each of the two reliability trials involving walking and running on the treadmill the $\dot{V}_E$, $\dot{V}O_2$ and $\dot{V}CO_2$ were averaged over the last 3 min of exercise.

Instrument

The VmaxST is a lightweight portable metabolic measurement system (120×110×45 mm; 650 g) that uses breath-by-breath technology [4,27]. It is composed of a facemask that fits over the nose and mouth, a volume turbine to measure flow (Triple® V, digital), a gas sample line that measures O₂ (electrochemical cell) and CO₂ (infrared analyzer) concentrations in the expired air, and a battery-operated unit that is secured to the chest with a harness. Data are transmitted to a computer via telemetry for metabolic calculations using metabolic stress test software (Metasoft, Version 1.11).

Calibration

The VmaxST was calibrated prior to each exercise session according to the manufacturer's specifications. The O₂ and CO₂ analyzers were calibrated using a certified reference gas (15% O₂, 5% CO₂, balance N₂) and room air. The volume calibration was performed using a 3-L syringe. Calibration of the pressure analyzer was performed by entering the barometric pressure prior to each test with the pressure reading from a wall-mounted mercury barometer.

Statistical Analysis

Random effects models were used to calculate the Coefficient of Variation (CV), the Intraclass Correlation Coefficient (ICC), and the Coefficient of Determination (R²) [28]. The CV, ICC and R² were the primary outcomes of interest for the present study. The data were analyzed after log transformation of the values; this produces within-person standard deviations that are independent of the mean. From this analysis:

$$CV = \text{Root Mean Square Error} \cdot 100\%$$

$$ICC = \text{Between-person variance} / (\text{Between-person variance} + \text{Within-person variance})$$

In addition, we used paired t-tests to examine the mean between-trial differences for V_E, VO₂ and VCO₂. Bland-Altman plots were constructed to visually assess systematic bias between the repeated measurements [3]. In addition, ordinary least squares regression was performed between the individual difference scores and the individual mean scores for V_E, VO₂, and VCO₂ to test for systematic bias.

RESULTS

The means (±SD) for V_E, VO₂ and VCO₂ for all reliability trials are shown in Table 2. For all comparisons except VCO₂ at 3 mph, there were no between-trial differences. The CVs for VO₂ and V_E (~5–8%) were lower than those for VCO₂ (~10–12%). This observation was also true for the ICC, with values for V_E and VO₂ (~0.80–0.90) being consistently higher than the ICCs for VCO₂ (~0.70–0.80). For V_E, VO₂ and VCO₂, R² values consistently high, ~0.85–0.95.

Bland-Altman plots illustrated no systematic bias in repeated measures of VO₂, VCO₂, and V_E during the walking and running trials (figure 1). Ordinary least squares regression between the individual difference scores and the individual mean scores for V_E, VO₂ and VCO₂, respectively, also confirmed the absence of any systematic bias (all *p* > 0.05)

DISCUSSION

The primary finding of this study is that the VmaxST portable metabolic measurement system appears to be reliable for determination of V_E and VO₂ during exercise eliciting V_E and VO₂ up to at least ~56 and 2.2 l/min, respectively. Validity of the VmaxST has been assessed previously. Prieur et al. [27] reported that the VmaxST tended to underestimate V_E, VO₂ and

VCO₂ in comparison to the DB method and when using a gas exchange simulator, but nevertheless concluded that “in comparison with other equivalent systems, the VmaxST is a valid instrument for VO₂ measurement during exercise.” Brehm et al. [4] found that the VmaxST produced values for V_E, VO₂ and VCO₂ during exercise on a cycle ergometer that differed by less than 3% from the DB method, and that Bland-Altman analysis revealed no systematic bias. Neither of these studies assessed reliability of the instrument.

Very few reliability studies have been performed on portable metabolic measurement systems [2,6,18,24]. Measurements by portable devices may be vulnerable to more sources of error than in-laboratory stationary online systems [27], especially in view of the considerable movements of the system during exercise. Our data were intended to assess the reliability of the VmaxST under exercise conditions spanning a range of metabolic rates, including light-, moderate-, and vigorous-intensity physical activities (i.e., ~2–8 METs) for an untrained population men and women

Use of multiple analyses, including CV, ICC, and Bland-Altman plots has been recommended for reliability assessment [2,6,12]. Using the DB method during cycle ergometry, Crouter et al. [6] reported CVs of 8.5%, 5.3% and 6.0% for V_E, VO₂, and VCO₂, respectively. Also using the DB method during cycle ergometry, Carter and Jeukendrup [5] reported CVs of 5.1–5.7%, 3.3–5.1%, and 3.9–5.0% for V_E, VO₂ and VCO₂, respectively. Our CVs for V_E (5.3–6.8%) and VO₂ (5.5–7.6%) during the walking and running trials are similar to those for the “gold standard” DB method, but our CVs for VCO₂ (10.5–11.7%) are approximately twice as high as those reported for the DB method. A CV < 10% has been suggested to represent acceptable reliability [6].

As suggested by Atkinson et al. [2] we also used the ICC for reliability assessment. Our results for the ICCs are consistent with those of the CV. The ICCs for V_E (0.80–0.92) and VO₂ (0.77–0.90) were consistently higher than those for VCO₂ (0.70–0.81). Crouter et al. [6] and Carter and Jeukendrup [2] did not report ICCs along with their CV analysis. Our ICCs are lower than those reported by Meyer et al. [24] for the MetaMax I portable metabolic measurement system (0.97–0.99), but generally higher than those reported by Larsson et al. [16] for the MetaMax II (0.43–0.84). One plausible explanation for the large variation in reported ICCs is differences in methods of calculating the ICC [22].

Although we did not assess validity of the system, the VmaxST-obtained values for VO₂ during walking and running compare favorably with values reported in a number of independent investigations [1,9,10,13,20,21,24,25,30]. The average VO₂ at 2.0 mph of 10.7 ± 1.8 ml/kg/min by subjects in our study was slightly higher than that reported by Willis et al. (30) (using a TrueMax 2000; 10.0 ml/kg/min) and Martin et al. ([21] (mixing chamber; 9.6 and 9.8 ml/kg/min for active and sedentary, respectively), and about the same as the VO₂ of ~10.5 ml/kg/min reported by Malatesta et al. [20] using a Marquette MGA-110 mass spectrometer. At 3.0 mph, our subjects' average VO₂ of 13.7 ± 1.6 ml/kg/min is in the middle of a range of previously reported values, including 12.1 and 14.4 ml/kg/min using a Sormedics 2900 [1,13], 13.2 ml/kg/min using a TrueMax 2000 [30], and ~14 ml/kg/min with the DB method [9]. At our highest walking speed of 4.0 mph, our subjects' mean VO₂ of 19.7 ml/kg/min is consistent with the values of 18.6 to 20.3 ml/kg/min reported by others using automated systems [22, 30] and DB method [9]. Running at 6.0 mph our subjects' VO₂ averaged 32.1 ml/kg/min, which is near the middle of the range of values reported in the literature, ~30–37 ml/kg/min, using both automated systems [10,25] and DB method [9].

Strengths and limitations

The major strengths of this study are the relatively large sample size and the fact that we used several methods of analysis to assess reliability, including CV, ICC, and Bland-Altman plots.

Furthermore, the trials were performed on separate days, typically 2–7 days apart. This would tend to increase both biological and methodological variability. Although we used three different walking speeds and one running speed, the absolute $\dot{V}_E$, $\dot{V}O_2$ and $\dot{V}CO_2$ during these trials were not maximal. Thus we cannot comment on the reliability of the VmaxST during heavy or severe exercise involving very high ventilatory flow rates.

Conclusion

We conclude that the VmaxST is a reliable portable indirect calorimetry system for measurement of $\dot{V}_E$ and $\dot{V}O_2$ during exercise eliciting $\dot{V}_E$ and $\dot{V}O_2$ at least up to ~56 and 2.2 l/min, respectively. For participants in the present study this represented relative exercise intensities of up to ~75% of $\dot{V}O_{2peak}$. The system appears to be less reliable for measuring $\dot{V}CO_2$. Consequently, use of R values ($\dot{V}CO_2/\dot{V}O_2$) for estimation of substrate utilization may not be warranted.

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Figure 1. Bland-Altman plots of the differences between the two measurements for oxygen uptake (VO_2), carbon dioxide production (VCO_2) and ventilation (VE) during the walking and running trials. The horizontal lines represent the mean difference ± 2 SD.

Table 1

Subject characteristics

	Females (n=26)	Males (n=19)	Total (n=45)
Age (yr)	24.8 ± 4.8	26.9 ± 6.4	25.7 ± 5.6
Height (cm)	166.1 ± 5.2	179.7 ± 7.2	171.8 ± 9.1
Weight (kg)	62.2 ± 8.9	79.5 ± 10.4	69.6 ± 12.8
VO ₂ peak (ml/kg/min)	40.1 ± 6.8	42.2 ± 6.1	40.7 ± 6.9
Percent fat	25.9 ± 11.4	16.0 ± 7.4	21.7 ± 11.0

Table 2
Test-retest reliability of the VmaxST portable metabolic measurement system for oxygen uptake (VO_2), carbon dioxide production (VCO_2) and ventilation (V_E) during walking and running.

Variable	Trial 1	Trial 2	CV	ICC	R ²	p-value
Treadmill Walking/Running						
VO_2						
2 mph	0.73 ± 0.13	0.74 ± 0.13	7.47	0.81	0.90	0.224
3 mph	0.96 ± 0.15	0.93 ± 0.15	7.64	0.77	0.88	0.166
4 mph	1.36 ± 0.23	1.36 ± 0.22	6.56	0.85	0.92	0.943
6 mph	2.22 ± 0.39	2.22 ± 0.40	5.53	0.90	0.95	0.813
VCO_2						
2 mph	0.61 ± 0.17	0.59 ± 0.12	11.72	0.70	0.85	0.485
3 mph	0.79 ± 0.19	0.74 ± 0.15	11.11	0.71	0.85	0.007
4 mph	1.16 ± 0.31	1.11 ± 0.21	10.51	0.76	0.88	0.119
6 mph	2.07 ± 0.60	1.97 ± 0.45	10.48	0.81	0.91	0.073
V_E						
2 mph	18.91 ± 3.91	19.06 ± 2.95	6.88	0.80	0.90	0.513
3 mph	23.06 ± 3.64	22.57 ± 3.38	6.44	0.82	0.91	0.139
4 mph	32.84 ± 5.84	32.21 ± 4.81	5.85	0.86	0.93	0.167
6 mph	56.34 ± 10.11	56.44 ± 10.77	5.25	0.92	0.96	0.993