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Whole-body volume of oxygen consumption while walking: Agreement between measured and estimated values

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Abstract

Predictive equations are widely employed for estimating the volume of oxygen consumption (VO_2) while walking, which is ultimately employed to determine energy expenditure and tailor exercise prescription. This study aimed to test the agreement between the measured VO_2 and estimated VO_2 during a walking protocol on a treadmill at 3.5, 4.5, 5.5, and 6.5 km/h. Thirty-eight young adults (50% women) participated in this cross-sectional study. The Omnical (Maastricht Instruments, Maastricht, The Netherlands) and K5 (Cosmed, Rome, Italy) metabolic systems were used to measure VO_2. To determine the predictive equations, a comprehensive literature search was conducted using the MEDLINE database from May 2022 to July 2023. Seven predictive equations were found and included for estimating VO_2 values. We calculated the mean bias (mean difference between measured VO_2 and estimated VO_2) obtained at each speed using one-sample *t*-tests. We compared the VO_2 measured and estimated values using repeated measures analysis of variance and the Bland–Altman method. One-sample *t*-tests showed that all score errors were different from zero (ranging from 1.1 to 5.4 mL/kg/min). Thus, no predictive equation estimated similar VO_2 values in comparison with the Omnical and K5 metabolic systems at all intensities. However, the Weyand equation showed the lowest bias across all intensities (score error of 1.1 mL/kg/min). This study showed a lack of agreement between the Omnical and K5 systems compared to diverse

Antonio Clavero-Jimeno and Andres Marmol-Perez are equal contribution.

predictive equations specially designed to estimate VO_2 during walking. Nevertheless, based on our results, the Weyand equation should be the preferred option.

KEYWORDS
energy cost, formulas, indirect calorimetry, oxygen cost, prediction

Highlights

- The estimated VO_2 values derived from all predictive equations showed no agreement with VO_2 values measured by the Omnical and K5 metabolic systems, highlighting the importance of taking into account the error introduced by VO_2 walking predictive equations when estimating VO_2.
- The Weyand equation presented the lowest bias in comparison to the VO_2 measured by the Omnical metabolic cart, which is the gold-standard metabolic cart (i.e., system of reference).
- These findings may hold practical implications when transitioning from clinically based programs to exercise interventions tailoring or self-guided exercise programs in young adults. Moreover, these results can contribute to individualize exercise programs by sport scientists using freely available and affordable tools as predictive equations.

1 | INTRODUCTION

Indirect calorimetry is considered to be the gold standard technique for measuring gas exchange (i.e., whole-body volume of oxygen consumption [VO_2] and carbon dioxide production) (Chen et al., 2020a) in diverse scenarios (e.g., exercise or resting conditions). Measuring VO_2 by indirect calorimetry while walking has been employed in different areas and populations, including young adults, to better understand the physiological needs and hence, accurately tailor exercise prescription (Looney et al., 2019). Walking at a self-pace is broadly employed as a safe physical activity in lifestyle interventions aimed at improving general health and body composition by increasing daily energy expenditure (Bull et al., 2020; Haskell et al., 2007). Indirect calorimetry can be applied indoor and outdoor conditions, but most of metabolic systems are stationary or "semi-portable" (e.g., the Omnical metabolic cart), thus restricting their use to indoor testing. Considering this limitation, "portable" metabolic systems have been developed, enabling the measurement of gas exchange in field settings outside of indoor laboratory assessments (Macfarlane, 2017).

Unfortunately, access to indirect calorimetry is limited for the general population, personal trainers, clinicians, and fitness centers, as systems are relatively expensive and require trained staff for handling the equipment and data. Trying to overcome these limitations, predictive equations have become an alternative to estimate VO_2 during walking activities. The equations developed by Pandolf et al. (1977) and by the American College of sports medicine (ACSM) (Riebe et al., 2018) are probably the most used in literature, although other equations have also been proposed (De Müllenheim et al., 1985; Léger et al., 1984; Looney et al., 2019; Ludlow et al., 2017; Minetti et al., 1985; van der Walt et al., 1973; Weyand et al., 1985a; Workman et al., 1963). Most of predictive equations include anthropometric characteristics, sex, and external load (as a surrogate of intensity; e.g., the walking speed), among other factors and estimate the VO_2 as relative units (e.g., VO_2 per kilogram of body mass [ml/kg/min]).

Several studies (Looney et al., 2019; Stoedefalke et al., 2022; Weyand et al., 1985b; Xue et al., 2021) have been conducted to determine the agreement between the measured (using indirect calorimetry) and the estimated (using predictive equations) VO_2 while walking. In this regard, equations for estimating VO_2 of different activities, which ultimately estimate their energy expenditure need, are useful for monitoring exercise adaptations, guiding exercise prescriptions, planning exercise regime modifications, and improving body composition (e.g., whole-body fat mass loss). These aforementioned studies (Looney et al., 2019; Stoedefalke et al., 2022; Weyand et al., 1985b; Xue et al., 2021) showed that the equation by the ACSM (Riebe et al., 2018) underestimated the VO_2 by $\approx$ 1.0 mL/kg/min while walking at 4.8 km/h and at a treadmill slope of 2% and overestimated the VO_2 by $\approx$ 1.2 mL/kg/min at 4.8 km/h and at slopes of 4% and 6% compared to indirect calorimetry (Stoedefalke et al., 2022). Regarding the Pandolf equation, at intensities of 4.0 km/h, 5.0 km/h, and 6.0 km/h, the authors observed an underestimation of VO_2 by −2.0, −2.5, and −2.3 mL/kg/min, respectively, compared to indirect calorimetry (Xue et al., 2021). Furthermore, the Weyand equation has been illustrated to have the best concordance with indirect calorimetry at intensities of 5.0 km/h and 6.0 km/h showing mean differences of −1.1 and −1.2 mL/kg/min, respectively (Xue et al., 2021). Thus, considering all the above, for a 90 kg adult, these equations show a bias ranging from 27 to 68 kcal per hour in estimating walking energy expenditure cost, which could negatively impact the exercise prescription or monitoring the goal of the intervention.

Nevertheless, few research studies have determined the comparability between the measured VO_2 and the estimated VO_2 values using different metabolic systems, different predictive equations, and different walking intensities in the same piece of work. In fact, whether the disagreements between measured and estimated VO_2 values are entirely related to the indirect calorimetry systems, the predictive equations and/or the walking intensity remained elusive. In this regard, not all but some equations included anthropometric and walking intensity parameters within their factors to estimate the VO_2. Therefore, whether a better agreement between measured versus estimated VO_2 values yielded by equations including these parameters into the calculation deserves more attention.

The main purpose of this study was to determine the agreement between the measured VO_2 using two different metabolic systems (the Omnical stationary metabolic cart and the K5 portable metabolic system) and the estimated VO_2 (using different previously published predictive equations) values during a walking protocol on a treadmill at four different intensities (3.5, 4.5, 5.5, and 6.5 km/h) in young adults. We hypothesized that predictive equations considering predicted resting metabolic rate (RMR), anthropometric, and walking intensity parameters would present a better agreement with measured VO_2 values compared to equations that only consider treadmill speed and slope.

2 | METHODS

2.1 | Subjects

This cross-sectional study is part of a more exhaustive experiment (the ICEX project) in which 38 young adults participated. Briefly, the inclusion criteria were as follows: (i) aged ≥18 years; (ii) body mass index between ≥18.5 and ≤ 40.0 kg/m^2; (iii) neither being enrolled in a weight loss program nor following any restrictive nutritional program; (iv) abstaining from using any medication that may directly impact gas exchange; (v) not suffering from chronic and/or acute illness; and (vi) not being pregnant. Before enrolling, each participant verbally confirmed that they met the inclusion criteria and signed an informed consent. The study protocol and informed consent received approval from the Human Research Ethics Committee (2402/CEIH/2021) and were conducted in accordance with the Declaration of Helsinki (last revision in 2013).

2.2 | Study design and procedures

In the ICEX project, which employed a repeated measures design, gas exchange was measured on two nonconsecutive days (with a 48-h interval) at various walking intensities using two different metabolic systems: Omnical (Maastricht Instruments, Maastricht, The Netherlands) and K5 (Cosmed, Rome, Italy). For the present study, we used only the data obtained from the first study day.

Participants were instructed to arrive to the laboratory by motorized vehicle and to avoid any moderate or intense physical activity since waking up. In addition, they were advised to abstain from engaging in moderate (24 h) and vigorous (48 h) physical activity. They should avoid consuming any drug (48 h) or stimulant beverage (12 h) that may influence energy metabolism. These conditions were confirmed upon arrival at the laboratory. For female participants, we registered their menstrual cycle phase.

We conducted gas exchange measurements in different periods as detailed below. A face mask (Hans Rudolph Inc., Kansas City, Missouri, USA) was fitted onto both metabolic systems to collect participants' gas exchange throughout the entire test. The gas exchange measurement followed the manufacturers' instructions and was uninterrupted throughout the entire test. Participants were instructed to breathe normally and avoid talking during the entire test. The test was conducted under controlled ambient temperature and humidity and carbon dioxide (CO_2) concentration were also monitored (Carbon Dioxide Detector JD-112; Dongguan Jinlide Electronic Technology Co., Ltd., Dongguan, Guangdong, China).

Before each measurement, the Omnical and K5 metabolic systems were calibrated (in accordance with the manufacturers' recommendations) by the same researchers. For the Omnical metabolic cart, volume was calibrated automatically by the system, while for the K5 portable system, a 3 L syringe was used. Regarding gas analyzers, both systems were calibrated using standard gas concentration bottles (O_2 and CO_2 of 18% and 0.8% for Omnical and 16% and 5% for K5; nitrogen balance). In addition, for the Omnical metabolic cart, a weekly methanol burning test was conducted by the same researcher (JMAA) to test the system's accuracy and precision as recommended (Chen et al., 2020b; Schoffelen et al., 2018).

2.3 | Walking protocol

At the beginning, participants remained seated in a motionless position for at least 10 min before starting the walking protocol. Afterward, participants were fitted with a face mask that was connected to either the Omnical or the K5 metabolic systems for the collection and measurement of gas exchange. Subsequently, participants performed a 35 min treadmill (H/P/cosmos pulsar; H/P/cosmos sports and medical GmbH, Nussdorf-Traunstein, Alemania) walking test using the Omnical or the K5 metabolic systems. Irrespective of the metabolic system used, the walking protocol was identical. The protocol started with a 5 min acclimation phase where participants stood motionless, standing, on the treadmill. After that, participants walked at a speed of 3.5 km/h for 5 min, followed by a resting period of 2.5 min. This cycle of walking 5 min and resting 2.5 min was repeated three more times, with increments of 1.0 km/h per period. At the start of the walking protocol, participants stepped onto the treadmill and then stepped off it during the rest phase. The gas exchange was measured continuously throughout the walking protocol. Following a resting period of 10–15 min, participants performed the walking protocol a second time. Therefore, gas exchange measurements were recorded twice for each participant, with one measurement taken using Omnical and the other using K5. The order of the metabolic systems was randomly assigned and counterbalanced. Moreover, 15 s prior to the end of each walking and resting period, we assessed the participant's effort through a subjective rating scale of perceived exertion (RPE-CR10) (Borg et al., 2006).

2.4 | Anthropometric assessment

Participant's body mass and height were measured (Seca model 799, Electronic Column Scale, Hamburg, Germany), while participants were barefoot and wearing light clothes.

2.5 | Search strategy

To determine and select the predictive equations to estimate VO_2 values during walking, a literature search was conducted using the MEDLINE (via PubMed) database from May 2022 to July 2023. The initial search retrieved 501 articles and a total of 29 studies were sought for selecting VO_2 predictive equations in walking conditions.

Studies published using predictive equations to estimate VO_2 values during a walking protocol were eligible. The keywords used, as well as the search equations, can be seen in Table S1. In brief, we used "energy metabolism," "oxygen consumption," "metabolic cost," and "walk test" among other entry terms (see Table S1) with Boolean operators. Study inclusion criteria were as follows: (i) participants: adults (aged >18 years); (ii) study design: cross-sectional and longitudinal studies; (iii) exposure: walking (iv) outcome: oxygen consumption (i.e., VO_2); values; and (v) language: English or Spanish. Exclusion criteria were as follows: (i) studies including predictive equations created for individuals younger than 18 years old and/or unhealthy individuals; (ii) noneligible publication types such as editorials, comments, guidelines, or case reports; (iii) predictive equations created for moderate-to-vigorous exercises or other physical activities different than walking; and (iv) predictive equations compared with VO_2 values using other method different than indirect calorimetry (e.g., the Douglas bag). Based on the selection criteria, all studies were independently screened for inclusion/exclusion by two reviewers (ACJ and AMP) and disagreements were solved by consensus or involving a third researcher when necessary (JMA). A total of 15 potential predictive equations were retrieved after the screening of the different studies. Finally, a total of seven predictive equations were selected after applying the PICOS strategy (Table S2). Otherwise, eight equations were excluded as one was developed using the Douglas bag, three equations were exclusively for loaded walking (our protocol was unloaded), and four equations were used in running conditions (Figure S1).

2.6 | Measured and estimated VO_2 values

The measured VO_2 gas exchange data were exported to an Excel spreadsheet from each metabolic system. Later, the first 2 min from each walking phase were excluded and the remaining measured VO_2 was averaged. Afterward, the measured VO_2 was averaged for each participant, metabolic system, and speed, separately. Similarly, we estimated VO_2 using every predictive equation for each speed, separately. Finally, for the Weyand equation, the RMR was estimated using the Schofield equation (Schofield, 1985).

2.7 | Statistical analyses

Results are presented as mean ± standard deviation (SD), unless otherwise stated. Analyses were performed using the Statistical Package for the Social Sciences v.24 (SPSS Statistics, IBM Corporation). The level of significance was set at $p < 0.05$. Figures were created using the Graph Pad Prism software (v. 8.4.1). Of note, all analyses were performed for the Omnical and K5 systems separately.

For VO_2 data (i.e., measured by each metabolic system and estimated by each equation) obtained at each intensity (i.e., 3.5, 4.5, 5.5, and 6.5 km/h), we computed the *mean bias* (calculated as measured VO_2–estimated VO_2) and the 95% lower and upper limits of agreement (LoA) as proposed by Bland and Altman (Martin Bland et al., 1986). A mean bias closer to zero indicates higher agreement between the measured and estimated VO_2 values. We also calculated the coefficient of variation (CV) as follows: (SD/average) × 100. Afterward, repeated measures analysis of variance (ANOVA) was conducted to test mean differences (with post hoc Bonferroni analysis) between the measured and the estimated VO_2 values at each intensity.

In addition, we calculated a *score error* for each predictive equation separately. We firstly computed the difference between the measured and the estimated VO_2 in absolute values at each intensity (e.g., |measured VO_2 at 3.5 km/h–estimated VO_2 at 3.5 km/h|), separately. Then, we computed the score error as the sum of these absolute differences was divided by four. Finally, one-sample *t*-tests were used to study whether the score error obtained for each equation was different from the zero value.

3 | RESULTS

A total of 38 participants (50% women; 25.50 ± 3.60 years; and body mass index 24.50 ± 2.50 kg/m^2) were included in this study.

Compared to Omnical, significant differences were observed between the measured VO_2 values and the estimated by predictive equations ($P < 0.001$; Figure 1). Bonferroni post hoc analyses showed significant differences between all the measured and the estimated VO_2 values except for the VO_2 estimated by the Pandolf and Weyand equations at 3.5 km/h (Figure 1A), ACSM equation at 4.5 km/h (Figure 1B), Weyand equation at 4.5 km/h (Figure 1C), and Müllenheim equation at 6.5 km/h (Figure 1D). Regarding K5, significant differences were observed between the measured VO_2 and the estimated values ($P < 0.001$; Figure 2). Bonferroni post hoc analyses showed significant differences between all the measured and the estimated VO_2 values except for the VO_2 estimated by the Léger equation at 3.5 km/h (Figure 2A), Pandolf and Müllenheim equations at 4.5 km/h (Figure 2B), and Pandolf, Van der Walt, and Léger equations at 5.5 and 6.5 km/h (Figure 2C,D).

Table 1 displays the agreement between measured and estimated VO_2 values across predictive equations and intensities. At 3.5 km/h, mean bias between the Omnical and predictive equations ranged from −3.5 (Léger equation) to 0.3 mL/kg/min (Weyand equation) and the narrowest LoA were observed for the Weyand

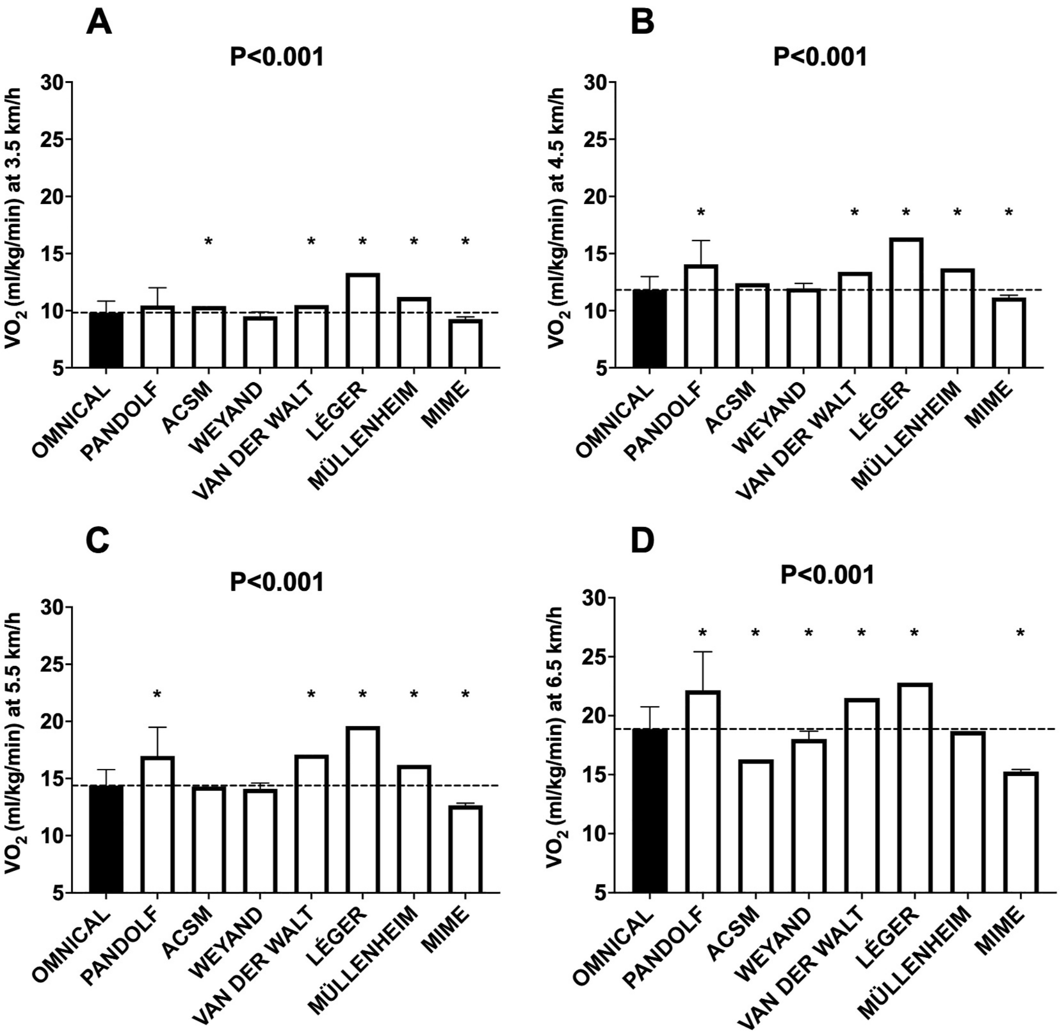

FIGURE 1 Whole-body volume of oxygen consumption (VO_2) measured by the Omnical (black column) and VO_2 estimated by the seven equations (white columns) while walking on a treadmill at different intensities. Panels A, B, C, and D show the VO_2 at 3.5, 4.5, 5.5, and 6.5 km/h, respectively. *p* values from repeated measures analysis of variance (ANOVA, ***n* = 38**). Asterisks (*) represent significant differences ($P < 0.05$ from post hoc Bonferroni analysis) between the measured VO_2 using Omnical versus the estimated VO_2. Dashed line represents the mean VO_2 value measured by Omnical. Results are presented as mean and standard deviation for Omnical's measured values, the Pandolf, Weyand, and MIME equations and as mean for the rest of equations. ACSM, American college of sports medicine; MIME, minimum mechanics; ml/kg/min, milliliters per kilogram of body mass per minute.

equation (−1.5 and 2.1) while, the widest for the Pandolf equation (−4.5 and 3.3). At 4.5 km/h, differences ranged from −4.6 (Léger) to 0.7 mL/kg/min (MIME equation) for Omnical (Table 1). The narrowest LoA were observed for Weyand (−2.2 and 2.0) while, the widest for the Pandolf equation (−7.3 and 2.8). At 5.5 km/h (Table 1), similar results to these observed at 4.5 km/h were obtained for the Omnical and K5 metabolic systems. At 6.5 km/h (Table 1), differences ranged from −3.3 (Pandolf) to 3.6 mL/kg/min (MIME equation) for Omnical. The narrowest LoA were observed for Weyand (−2.4 and 4.1) while, the widest for the Pandolf equation (−11.6 and 5.1). Concerning K5, differences ranged from 0.6 (Léger) to 8.2 mL/kg/min (MIME equation). Regarding LoA, the narrowest were observed for Weyand (−1.4 and 12.2) while, the widest for the Pandolf equation (−11.5 and 14.2). Overall, and regardless the walking speed, lower CV values were observed for the Omnical system (Table 1).

Concerning the score error computed for Omnical (Figure 3), one-sample *t*-tests showed that all score errors were different from the zero value (all $P < 0.001$). Similar results (all $P < 0.001$) were observed for K5 (Figure 3), although the observed score errors were slightly higher (~2 mL/kg/min; Figure 3) than those observed for Omnical.

4 | DISCUSSION

The findings of this study indicated that there was no agreement between measured VO_2 values by metabolic systems and estimated VO_2 values by predictive equations in young adults while walking at four different intensities (3.5, 4.5, 5.5, and 6.5 km/h) as suggested by the mean bias values obtained. Noteworthy, the score error

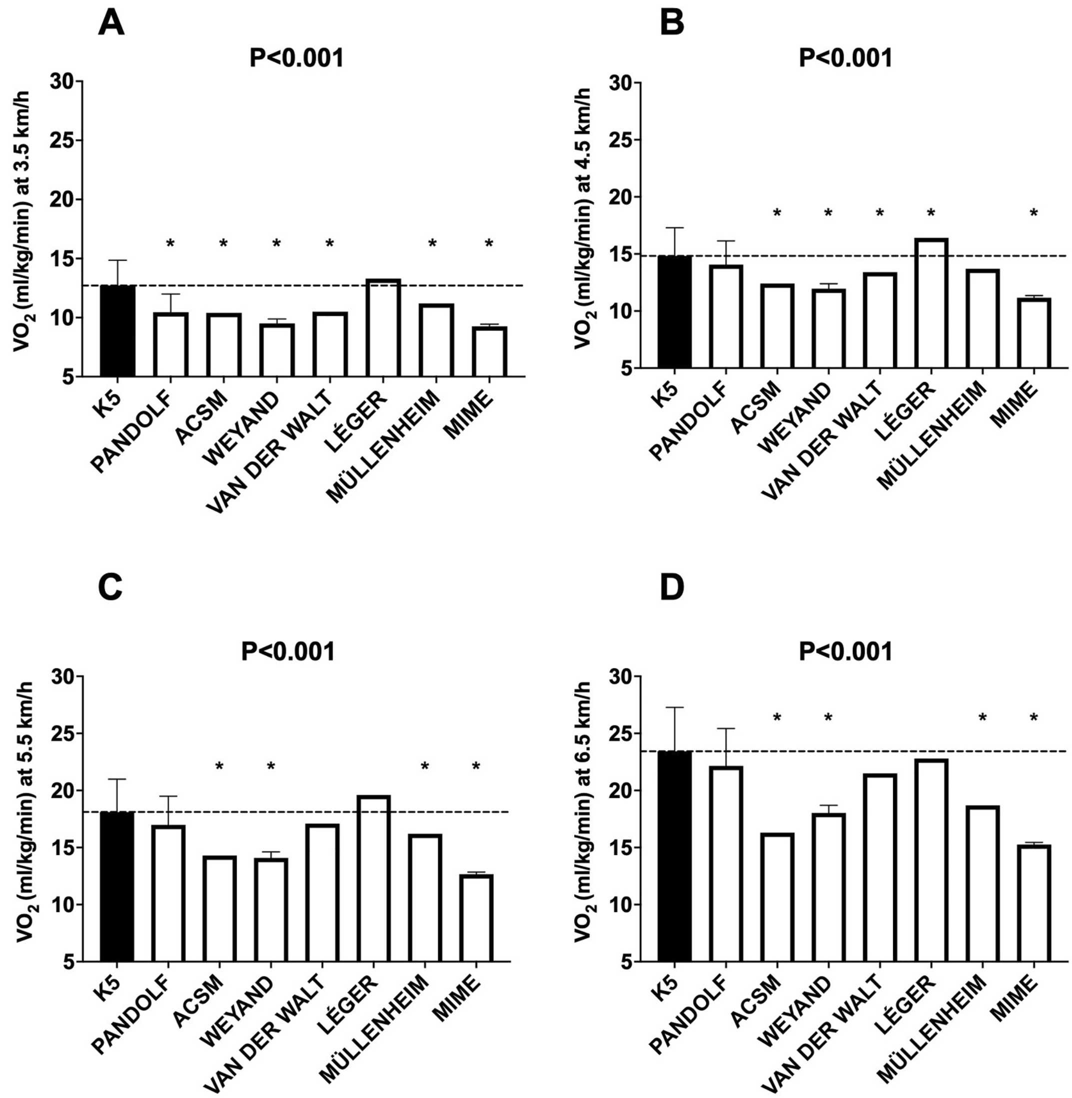

FIGURE 2 Whole-body volume of oxygen consumption (VO_2) measured by K5 (black column) and VO_2 estimated by the seven equations (white columns) while walking on a treadmill at different intensities. Panels A, B, C, and D show the VO_2 at 3.5, 4.5, 5.5, and 6.5 km/h, respectively. *p* values from repeated measures analysis of variance (ANOVA, $\boldsymbol{n} = \mathbf{38}$). Asterisks (*) represent significant differences ($P > 0.05$ from post hoc Bonferroni analysis) between the measured VO_2 using K5 versus the estimated VO_2. Dashed line represents the mean VO_2 value measured by K5. Results are presented as mean and standard deviation for K5's measured values, the Pandolf, Weyand, and MIME equations and as mean for the rest of equations. ACSM, American college of sports medicine; MIME, minimum mechanics; ml/kg/min, milliliters per kilogram of body mass per minute.

computed as a surrogate of the "total error" including all intensities that did not retrieve a clear pattern concerning the increase/decrease of the error between measured and estimated VO_2 values. However, it should be noted that the Weyand equation showed the lowest error as suggested by the score error when estimating VO_2 in comparison to the measured values obtained by the Omnical metabolic cart. Consequently, we would recommend the use of the Weyand equation for estimating VO_2 in walking conditions in young adults.

The VO_2 is directly related to body mass—the heavier the subject, the higher is its consumption—and to exercise intensity—the higher the intensity, the higher the VO_2 demands. Thus, most predictive equations include these factors to estimate VO_2. On the other hand, metabolic systems present different validity and accuracy (Alcantara et al., 2018, 2022; Larsson et al., 2004; Ludlow et al., 1985; Martin Bland et al., 1986). For that reason, it is plausible that the concordance between the measured VO_2 and the estimated VO_2 values using different metabolic systems and predictive equations may vary. Unfortunately, the literature determining these issues in the same piece of work is scarce. In our study, when using the Omnical metabolic cart, we observed significant differences between the measured and the estimated VO_2 values as well as remarkably mean bias and wide LoA. Based on our findings, at 3.5 km/h and 4.5 km/h, most equations underestimated VO_2 values in walking conditions. However, the Weyand equation retrieved the VO_2 estimation most similar to the measured VO_2 values by Omnical

TABLE 1 Mean bias (shown as ml/kg/min) and coefficient of variation (CV; shown as percentage) between measured VO_2 and estimated VO_2 using predictive equations by the intensity at which the walking protocol was elicited.

	Omnical			K5		
Intensity	Mean bias (SD)	95% LoA (lower, upper)	CV	Mean bias (SD)	95% LoA (lower, upper)	CV
3.5 km/h						
Pandolf	−0.6 (2.0)	(−4.5, 3.3)	11.8 (7.9)	2.3 (3.3)	(−4.1, 8.6)	18.2 (14.4)
ACSM	−0.6 (1.0)	(−2.6, 1.4)	7.0 (4.6)	2.3 (2.1)	(−1.9, 6.5)	14.3 (9.2)
Weyand	0.3 (0.9)	(−1.5, 2.1)	5.5 (3.9)	3.2 (2.1)	(−0.9, 7.3)	16.3 (9.2)
Van der Walt	−0.7 (1.0)	(−2.7, 1.3)	7.2 (5.0)	2.2 (2.1)	(−2.0, 6.4)	13.5 (9.1)
Léger	−3.5 (1.0)	(−5.5, 1.5)	21.6 (7.0)	−0.6 (2.1)	(−4.8, 3.6)	9.5 (7.9)
Müllenheim	−1.4 (1.0)	(−3.4, 0.6)	10.0 (6.5)	1.5 (2.1)	(−2.7, 5.7)	11.0 (8.1)
MIME	−0.6 (1.0)	(−1.3, 2.4)	6.2 (4.5)	3.5 (2.2)	(−0.8, 7.7)	20.9 (10.8)
4.5 km/h						
Pandolf	−2.2 (2.6)	(−7.3, 2.8)	15.0 (10.1)	0.8 (4.1)	(−7.2, 8.8)	16.8 (11.0)
ACSM	−0.6 (1.2)	(−2.9, 1.7)	6.4 (4.6)	2.4 (2.5)	(−2.4, 7.3)	13.8 (8.6)
Weyand	−0.1 (1.1)	(−2.2, 2.0)	5.8 (4.3)	2.9 (2.3)	(−1.7, 7.4)	13.6 (8.3)
Van der Walt	−1.6 (1.2)	(−3.9, 0.7)	9.8 (6.1)	1.4 (2.5)	(−3.4, 6.3)	10.9 (7.3)
Léger	−4.6 (1.2)	(−6.9, 2.3)	23.3 (6.8)	−1.6 (2.5)	(−6.4, 3.3)	11.3 (8.8)
Müllenheim	−1.9 (1.2)	(−4.2, 0.4)	11.1 (6.5)	1.1 (2.5)	(−3.7, 6.0)	10.3 (7.1)
MIME	0.7 (1.1)	(−1.6, 2.9)	6.0 (4.7)	3.7 (2.4)	(−1.1, 8.5)	18.9 (11.1)
5.5 km/h						
Pandolf	−2.6 (3.2)	(−8.8, 3.6)	14.7 (10.1)	1.1 (4.8)	(−8.3, 10.6)	16.1 (11.9)
ACSM	0.1 (1.4)	(−2.7, 2.8)	5.4 (4.1)	3.8 (2.9)	(−1.8, 9.5)	17.0 (9.3)
Weyand	0.3 (1.3)	(−2.2, 2.8)	5.1 (3.7)	4.0 (2.7)	(−1.2, 9.2)	16.9 (9.2)
Van der Walt	−2.7 (1.4)	(−5.5, 0.0)	12.7 (6.4)	1.0 (2.9)	(−4.6, 6.7)	9.5 (7.2)
Léger	−5.2 (1.4)	(−8.0, −2.5)	22.0 (6.7)	−1.5 (2.9)	(−7.1, 4.2)	9.8 (8.9)
Müllenheim	−1.8 (1.4)	(−4.6, 0.9)	9.3 (5.9)	1.9 (2.9)	(−3.7, 7.6)	11.3 (7.3)
MIME	1.7 (1.4)	(−0.9, 4.4)	9.5 (5.4)	5.4 (2.9)	(−0.2, 11.0)	24.4 (10.2)
6.5 km/h						
Pandolf	−3.3 (4.3)	(−11.6, 5.1)	15.0 (9.6)	1.4 (6.5)	(−11.5, 14.2)	16.8 (12.5)
ACSM	2.6 (1.9)	(−1.1, 6.3)	10.3 (6.3)	7.1 (3.9)	(−0.4, 14.7)	25.4 (9.5)
Weyand	0.9 (1.7)	(−2.4, 4.1)	6.2 (4.9)	5.4 (3.5)	(−1.4, 12.2)	20.7 (8.5)
Van der Walt	−2.6 (1.9)	(−6.3, 1.1)	10.4 (5.3)	1.9 (3.9)	(−5.6, 9.5)	10.4 (8.3)
Léger	−3.9 (1.9)	(−7.6, −0.2)	14.1 (5.7)	0.6 (3.9)	(−6.9, 8.2)	9.2 (8.2)
Müllenheim	0.2 (1.9)	(−3.5, 3.9)	4.9 (4.6)	4.7 (3.9)	(−2.8, 12.3)	16.6 (9.7)
MIME	3.6 (1.9)	(−0.1, 7.3)	14.6 (6.6)	8.2 (3.8)	(0.7, 15.6)	29.6 (9.5)

Note: Results are presented as mean bias (measured value minus estimated value) and standard deviation (SD), 95% limits of agreement (LoA; lower and upper limits), and CV and its SD.

Abbreviations: ACSM, American college of sports medicine; MIME, minimum mechanics; ml/kg/min, milliliters per kilogram of body mass per minute; VO_2, whole-body volume of oxygen consumption.

metabolic cart at all intensities. These results were aligned with previous literature (Ludlow et al., 1985, 2017; Xue et al., 2021) showing that, at low intensity exercise in young adults, the Weyand predictive equation was the most concordant equation with measured VO_2 compared to these values retrieved by the ACSM and Pandolf equations. These results were reinforced by the lower CVs yielded by the VO_2 values estimated by the Weyand equation compared to the measured by the Omnical metabolic cart. Our results were similar to those observed in previous literature, as we observed certain bias when using the ACSM and Pandolf equation (Hasegawa et al., 2007; Looney et al., 2019; Ludlow et al., 1985, 2017; Montoye et al., 1985; Stoedefalke et al., 2022; Xue et al., 2021).

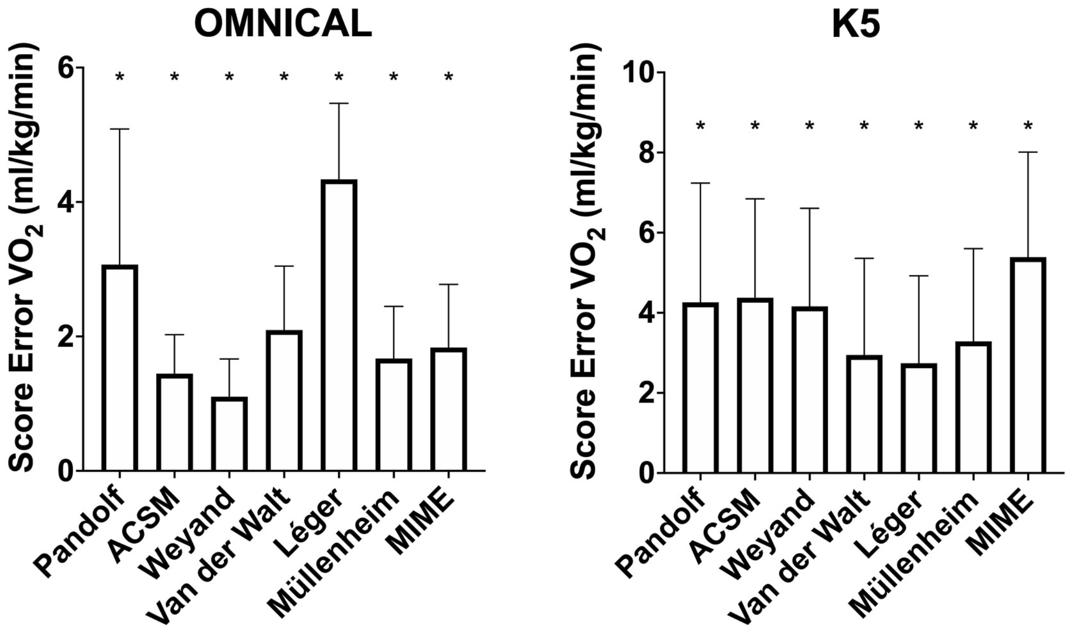

FIGURE 3 Score error (mean error of the four intensities of each predictive equation for the VO_2 estimation) in absolute values along the four intensities (3.5 km/h, 4.5 km/h, 5.5 km/h, and 6.5 km/h) in comparison to mean VO_2 consumption measured by Omnical (left) and K5 (right) along the four intensities. Asterisks (*) represent significant differences of the score error of the predictive equations from the zero value ($P < 0.05$ from one-sample t-test). Results are presented as mean and standard deviation. ACSM, American College of Sports Medicine; MIME, Minimum Mechanics; ml/kg/min, milliliters per kilogram of body mass per minute, VO_2, whole-body volume of oxygen consumption.

Regarding the Van der Walt, Léger, Müllenheim, and MIME predictive equations, previous literature comparing their performance against other equations and/or metabolic systems is scarce; thus, rendering comparisons between studies impossible. However, it should be noted that predictive equations showed a different agreement compared to the Omnical metabolic cart depending on the intensity at which the walking was elicited (e.g., the MIME equation showed a mean bias of –0.6 at 3.5 km/h and of 3.6 at 6.5 km/h, respectively). Therefore, to compute all the errors across intensities in a single outcome, we calculated the *score error*. For Omnical, we observed that the Weyand (mean score error of 1.1 mL/kg/min) equation obtained the lowest differences compared to the measured VO_2 values. For example, considering an individual weighted 80 kg, the Weyand equation biased the estimation of VO_2 while walking by 0.44 kcal per minute (26 kcal per hour). Thus, we considered this equation the best when estimating VO_2. Conversely, the Léger equation obtained the largest differences compared to the measured values (mean score error of 4.3 mL/kg/min), which suggest that the Léger equation should be used with caution as may produce biased walking VO_2 estimations (following the abovementioned example, the error would be 103 kcal per hour).

Similarly, we observed differences between the measured VO_2 by K5—a device that have been tested to be valid and reliable in outdoor settings (Martin Bland et al., 1986)—and the estimated VO_2 values as well as remarkably mean bias and wide LoA. To our knowledge, to date, no studies have investigated these measured versus estimated VO_2 comparison using the K5 system. At the lowest intensity (3.5 km/h), all the predictive equations, except the Léger equation, overestimated the VO_2 compared to measured values by K5. Similarly, after increasing the walking intensity (4.5 and 5.5 km/h), same results were observed. Given the lack of studies examining the agreement between the VO_2 measured by the K5 system and Léger predictive equation, it is not possible to further compare this observation we made. However, in agreement with the Omnical results, the Léger predictive equation also underestimated the VO_2 across intensities. However, it should be noted that at 6.5 km/h, the Léger predictive equation yielded the most similar estimation compared to the measured values by K5. Contrary to our findings, (Weyand et al., 1985b) showed that MIME predictive equation had the lowest mean differences (0.02 mL/kg/min) in comparison with the $K4b^2$ system (which is the previous version of the K5 system), whereas our results suggest that the MIME predictive equation had the highest mean bias at this intensity and CV. Of note, the study by (Weyand et al., 1985b) included only seven subjects and followed an outdoor protocol in a field course that varied in gradient (−3 to +5%) and terrain (asphalt and grass) at self-selected speeds. Thus, these differences between study protocols (e.g., $K4b^2$system vs. K5 system, outdoor vs. indoor, field course vs. treadmill, and self-selected speeds vs. fixed speeds) may, at least in part, explain disagreements between results. Concerning the *score error*, for the K5 portable system, we observed that the Léger (mean score error of 2.7 mL/kg/min) equation obtained the lowest differences compared to the measured VO_2 values (error 65 kcal per hour). On the contrary, the MIME predictive equation showed the highest score error (mean score error of 5.4 mL/kg/min and error 130 kcal per hour). Due to the lack of studies addressing the agreement between measured VO_2 versus estimated VO_2 while walking, using different devices and predictive equations, future studies are warranted. Moreover, these predictive equations have been widely used to estimate energy expenditure, whereas VCO_2 is required to accurately perform this estimation (Gill et al., 1985). Thus, more equations are needed in order to estimate energy expenditure combining VO_2 and VCO_2.

This study has some limitations that need to be considered. Firstly, we only included young adults; therefore, we cannot know whether our results are transferable to clinical populations, children, adolescents, and/or older adults. However, having a homogenous sample is a strength of this study to avoid possible cofounding factors related to aging (e.g., decrease of VO_2). We analyzed the VO_2 in well-controlled laboratory conditions, so we do not know the real application of these predictive equations in outdoor and/or free-living conditions. We included two metabolic systems that may not represent all the metabolic systems in this field. Nonetheless, we used the Omnical metabolic cart, a system that may be considered as the gold standard device for measuring gas exchange as suggested by recent literature (Alcantara et al., 2022, 2023; Kaviani et al., 2018; Schoffelen et al., 2019). The treadmill slope was always fixed at 1% and when estimating VO_2 values from predictive equations, this could have incurred a statistical error for predictive equations that did not take the slope into account. We did not control the menstrual cycle of women; however, due to the within-subject study design, this issue should not influence the results. Moreover, previous studies have reported no effect of menstrual cycle on energy expenditure during submaximal exercise (Frandsen et al., 1985; Williams et al., 2023). Finally, we did not standardize the last meal composition and/or amount. Nevertheless, participants were instructed to come to the laboratory in the same fasting status (>3–4 h), and as previously mentioned, the within-subject design may minimize its possible influence.

5 | CONCLUSIONS

The main findings of this study showed that there was no agreement between measured VO_2 values by the two metabolic systems used (Omnical and K5) and estimated VO_2 values by predictive equations at four different intensities (3.5, 4.5, 5.5, and 6.5 km/h) in young adults. Our study suggests that the Weyand equation should be the preferred option for estimating VO_2 while walking in young adults, as it presented the lowest bias and error.

AUTHOR CONTRIBUTIONS

The authors' responsibilities were as follows – Antonio Clavero-Jimeno, Andres Marmol-Perez, Jonatan R. Ruiz and Juan M. A. Alcantara: designed the study; Antonio Clavero-Jimeno, Andres Marmol-Perez and Juan M. A. Alcantara: analyzed the data; Antonio Clavero-Jimeno and Andres Marmol-Perez: wrote the original draft; Antonio Clavero-Jimeno, Andres Marmol-Perez, Manuel Dote-Montero, Jonatan R. Ruiz and Juan M. A. Alcantara: revised the manuscript and discussed the results; Antonio Clavero-Jimeno, Andres Marmol-Perez, Jonatan R. Ruiz and Juan M. A. Alcantara: were primarily responsible for the final content. Finally, all authors read and approved the final version.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest.

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