Energy expenditure equation choice: effects on cycling efficiency and its reliability

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Running head: Energy expenditure & cycling efficiency

Submission type: Brief report

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Abstract word count: 250

Text-only word count: 1686

Number of figures and tables: 3

References: 13

Abstract

Purpose: There are several published equations to calculate energy expenditure (EE) from gas exchanges. We assessed whether using different EE equations would affect gross efficiency (GE) estimates and their reliability. **Methods:** Eleven male and three female cyclists (age: 33 ± 10 years; height: 178 ± 11 cm; body mass: 76.0 ± 15.1 kg; maximal oxygen uptake: 51.4 ± 5.1 $ml \cdot kg^{-1} \cdot min^{-1}$; peak power output: 4.69 ± 0.45 $W \cdot kg^{-1}$) completed five visits to the laboratory on separate occasions. In the first visit, participants completed a maximal ramp test to characterize their physiological profile. In visits two to five, participants performed four identical submaximal exercise trials to assess GE and its reliability. Each trial included three 7-min bouts at 60%, 70% and 80% of the gas exchange threshold. EE was calculated with four equations by Péronnet & Massicotte, Lusk, Brouwer and Garby & Astrup. **Results:** All four EE equations produced GE estimates that differed from each other (all $P < 0.001$). Reliability parameters were only affected when the typical error was expressed in absolute GE units, suggesting a negligible effect—related to the magnitude of GE produced by each EE equation. The mean coefficient of variation for GE across different exercise intensities and calculation methods was 4.2%. **Conclusions:** Although changing the EE equation does not affect GE reliability, exercise scientists and coaches should be aware that different EE equations produce different GE estimates. Researchers are advised to share their raw data to allow for GE recalculation, enabling comparison between previous and future studies.

Keywords: gross efficiency, cycling economy, metabolic rate, respiratory exchange ratio, measurement error

Introduction

Cycling efficiency describes the relationship between mechanical power output and metabolic power input, and it is a determinant of endurance performance [1]. Hence, gross efficiency (GE), the most valid index of cycling efficiency [1], can be expressed by:

$$GE\ (\%) = [\text{mechanical power output } (J \cdot s^{-1}) / \text{metabolic power input } (J \cdot s^{-1})] \cdot 100 \qquad (1)$$

Different work rate units can be directly converted to $J \cdot s^{-1}$. In contrast, the metabolic power input, which represents a rate of energy expenditure (EE), can be estimated from several methods. In the cycling efficiency literature, four main equations that calculate EE from gas exchanges under steady-state conditions (see methods) have been used [2-5].

Recently, Kipp et al. [6] compared ten published equations when calculating the EE of running bouts. The equation by Péronnet & Massicotte [7] produced the highest EE estimates [6]. Accordingly, Kipp et al. [6] recommended that researchers use Péronnet & Massicotte [7] for its meticulous account of the energy provided from glucose and fat oxidation, based on the latest chemical and physical data available at their time. However, the extent to which different EE equations affect GE in cycling is unknown, suggesting further investigation on this topic is necessary.

While the inverse relationship between EE and GE is evident, it is less clear whether using different EE equations would affect GE reliability. Yet, differences in measurement 'noise' associated with each EE equation would make cycling efficiency studies hard to compare—increasing uncertainty levels, even if the magnitude of GE is minimally impacted.

We tested the hypothesis that GE estimates and their reliability would be affected by EE equation choice.

Methods

Participants

Eleven male and three female cyclists [age: 33 ± 10 years; height: 178 ± 11 cm; body mass: 76.0 ± 15.1 kg; maximal oxygen uptake ($\dot{V}O_{2max}$): 51.4 ± 5.1 $ml \cdot kg^{-1} \cdot min^{-1}$; peak power output (PPO): 4.69 ± 0.45 $W \cdot kg^{-1}$] participated in this study after providing written informed consent. The institution's ethics committee approved the study in compliance with the Declaration of Helsinki.

Design

Participants completed five visits to the laboratory on separate occasions at least 48 h apart. In the first visit, participants completed a maximal ramp test to characterize their physiological profile. In visits two to five, participants performed four identical submaximal exercise trials to assess GE and its reliability. Participants were instructed to refrain from exercise, alcohol and caffeine for 24 h before each visit.

Ramp test

The test started with a 10-min warmup at 100 W for men, and 50 W for women. Subsequently, work rate increased continuously at 25 $W \cdot min^{-1}$ until voluntary exhaustion, or participants' inability to maintain cadence above 70 $rev \cdot min^{-1}$. $\dot{V}O_{2max}$ was calculated as the highest 30-s mean, and PPO as the mean power output of the last minute. Gas exchange threshold (GET) was calculated according to the procedures described by Lansley et al. [8], as the first disproportionate increase in carbon dioxide output ($\dot{V}CO_2$) vs. oxygen uptake ($\dot{V}O_2$); an increase in ventilatory equivalent for oxygen, with no increase in ventilatory equivalent for carbon dioxide; and an increase in end-tidal oxygen tension with no fall in end-tidal carbon dioxide tension. Two-thirds of the ramp rate was deducted from the work rate at GET to account for the $\dot{V}O_2$ mean response time.

Submaximal trials

Participants performed three 7-min bouts consecutively at 60%GET, 70%GET, and 80%GET (34 ± 4%, 39 ± 5%, and 45 ± 5% PPO). Cyclists were required to report their preferred cadence and hold it constant throughout the study (86 ± 6 $rev \cdot min^{-1}$). During the last 60 s of each bout, ratings of perceived exertion (RPE) and blood lactate concentration ([La]) were measured. GE was calculated from the mean gas exchanges ($L \cdot min^{-1}$) in the last 3 min of each 7-min bout according to Equation 1. All participants fulfilled the criteria of a respiratory exchange ratio (RER) ≤ 1.0 in all trials. EE ($J \cdot s^{-1}$) was estimated assuming negligible protein oxidation, according to:

Péronnet & Massicotte [7]:

$$EE = 281.67\dot{V}O_2 + 80.65\dot{V}CO_2 \qquad (2)$$

Lusk [9]:

$$EE = 266.16\dot{V}O_2 + 85.95\dot{V}CO_2 \qquad (3)$$

Brouwer [10]:

$$EE = 269.93\dot{V}O_2 + 83.37\dot{V}CO_2 \qquad (4)$$

Garby & Astrup [11]:

$$EE = 267.33\dot{V}O_2 + 82.33\dot{V}CO_2 \qquad (5)$$

Equipment

All tests were performed on the participants' own bike, attached to an ergometer (Cyclus 2, RBM Elektronik-Automation, Leipzig, Germany). Breath-by-breath gas exchanges were continuously monitored (MetaLyzer 3B, Cortex Biophysik, Leipzig, Germany). Prior to each test, calibration was performed according to the manufacturer's instructions.

Statistical analysis

All variables were assessed for normality using Shapiro-Wilk tests. Two-way repeated measures analyses of variance (equation × trial) were performed to test for differences in GE and EE separately at each exercise intensity. One-way repeated measures analyses of variance (trial) were performed to test for differences in RPE and [La]. Following analysis of variance, Bonferroni pairwise comparisons were used to identify where significant differences existed within the data. Partial eta-squared (η^2_p) was computed as effect size estimates. Significance level was set at $P \leq 0.05$. Data were analyzed using SSPS Statistics 25 (IBM, Armonk, USA). Reliability was quantified by typical errors in absolute GE units, coefficients of variation and intraclass correlation coefficients produced by a freely available spreadsheet [12].

Results

There was an interaction between equation and trial for GE at 70%GET ($F = 3.49$; $P = 0.033$; $\eta^2_p = 0.21$) and 80%GET ($F = 3.28$; $P = 0.044$; $\eta^2_p = 0.20$), but not at 60%GET ($F = 2.44$; $P = 0.099$; $\eta^2_p = 0.16$). No interactions were found for EE (all intensities $F < 2.56$; $P > 0.077$; $\eta^2_p < 0.20$).

There was a main effect of equation for both GE (all intensities $F > 1659.87$; $P < 0.001$; $\eta^2_p > 0.99$) and EE (all intensities $F > 203.46$; $P < 0.001$; $\eta^2_p > 0.94$). All pairwise comparisons were different from each other for both GE (all $P < 0.001$) and EE (all $P < 0.001$).

A main effect of trial was found at 70%GET for both GE ($F = 3.76$; $P = 0.030$; $\eta^2_p = 0.22$) and EE ($F = 3.34$; $P = 0.048$; $\eta^2_p = 0.20$). Bonferroni pairwise comparisons revealed that trial 1 was different from trials 2 and 3 (all $P < 0.047$) for GE, and different from trial 2 for EE ($P = 0.037$). At 60%GET and 80%GET, there was no main effect of trial for both GE and EE (all $F < 2.98$; $P > 0.064$; $\eta^2_p < 0.19$).

[Figure 1]

The reader is referred to the raw data repository (http://osf.io/9xhva) for further exploration of the relationship between EE and GE.

Reliability parameters are presented in Table 1. RPE and [La] in each trial are presented in Table 2. A main effect of trial was found at 70%GET for both RPE ($F = 2.91$; $P = 0.0.045$; $\eta^2_p = 0.16$) and [La] ($F = 3.69$; $P = 0.045$; $\eta^2_p = 0.20$). Bonferroni pairwise comparisons revealed that trial 3 was different from trial 4, but for [La] only ($P = 0.037$). At 60%GET and 80%GET, there was no main effect of trial for both RPE and [La] (all $F < 2.09$; $P > 0.115$; $\eta^2_p < 0.12$).

[Table 1]
[Table 2]

Discussion

All exercise bouts in this study were performed under steady-state condition, which is a prerequisite to measure cycling efficiency from gas exchanges [1]. According to our hypothesis, different EE equations produced different GE estimates. As expected, Péronnet & Massicotte [7] equation produced the lowest GE. However, reliability parameters were only affected when the typical error was expressed in absolute GE units, suggesting a negligible effect—related to the magnitude of GE produced by each EE equation.

To illustrate the impact of EE equation on GE, assume a cyclist exercising at a metabolic rate of 1000 $J \cdot s^{-1}$, and negligible contribution from the anaerobic metabolism to ATP turnover. Considering the mean GE we found at 80%GET (i.e. 20.6% [7], 21.2% [9], 21.1% [10], and 21.4% [11]), the cyclist would produce 206, 212, 211, and 214 W, respectively. Clearly, the EE equation choice is important to modelling endurance cycling performance. Our results also suggest GE calculations must be standardised to allow comparability between cycling efficiency studies. We therefore reinforce the recommendations of Kipp et al. [6] that researchers abandon outdated equations with incorrect assumptions. Moreover, the raw data from previous and future studies should be provided, allowing for GE recalculation even if new equations are devised.

GE is recognised as an endurance performance determinant [1]. However, less scientific efforts have been directed toward understanding how to improve GE in comparison to $\dot{V}O_{2max}$ and lactate/ventilatory thresholds. One possible reason may be the lack of standard procedures to measure GE, which confounds the interpretation of published literature. Accordingly, this report should be viewed as an extension of the guidelines proposed by our group [1], given the choice for the EE equation was not discussed in that work. As the analysis of GE produced some significant differences where EE did not, we also recommend that GE is used in cycling-based studies rather than EE or metabolic rates to express cycling economy. GE takes into account power output, producing a more sensitive measure particularly when researchers adopt relative exercise intensities.

Assessing the variability of GE across repeated measures is important to clarify the precision with which GE changes can be detected. Accordingly, our results suggest different EE equations do not affect GE reliability when its magnitude is taken into account (i.e. coefficient of variation). That said, the mean coefficient of variation for GE across different exercise intensities and calculation methods was 4.2%, which is typical for breath-by-breath gas analysis systems (4.2% [13], 4.4% [5]), but not as reliable as GE estimated through the Douglas bag method (1.5% [2]).

Practical Applications

As the EE equation choice does not affect GE reliability, exercise scientists and coaches can be assured that the cycling efficiency literature is trustworthy. However, it is important to bear in mind that the lack of uniformity in EE equation choice affects the magnitude of GE estimates, precluding direct data comparison. Researchers are advised to avoid outdated EE equations, and to share their raw data to allow for GE recalculation, enabling comparison between previous and future studies.

Conclusions

Although changing the EE equation does not affect GE reliability, it does alter the magnitude of GE estimates.

Acknowledgements

The authors would like to thank the cyclists that participated in this study.

Funding: AHB is a CNPq—Brazil scholarship holder. The results of the current study do not constitute an endorsement of the product by the authors or the journal.

Disclosure of Conflict of Interests: The authors have no conflict of interests.

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Figure Captions

Figure 1 – Gross efficiency at 60% (panel a), 70% (panel b) and 80% (panel c), and energy expenditure at 60% (panel d), 70% (panel e) and 80% (panel f) of the power output associated with the gas exchange threshold. Data are expressed as mean ± standard deviation, separated by exercise trial and energy expenditure equation: Péronnet & Massicotte [7] (black bar), Lusk [9] (dotted bar), Brouwer [10] (white bar) and Garby & Astrup [11] (striped bar). † denotes significant differences between all equation comparisons. * denotes significant difference from trial 1. § denotes interaction between equation and trial.