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

2

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32 **Abstract**

33 **Purpose:** There are several published equations to calculate energy expenditure (EE)
34 from gas exchanges. We assessed whether using different EE equations would affect
35 gross efficiency (GE) estimates and their reliability. **Methods:** Eleven male and three
36 female cyclists (age: 33 ± 10 years; height: 178 ± 11 cm; body mass: 76.0 ± 15.1 kg;
37 maximal oxygen uptake: 51.4 ± 5.1 ml·kg⁻¹·min⁻¹; peak power output: 4.69 ± 0.45
38 W·kg⁻¹) completed five visits to the laboratory on separate occasions. In the first visit,
39 participants completed a maximal ramp test to characterize their physiological profile.
40 In visits two to five, participants performed four identical submaximal exercise trials to
41 assess GE and its reliability. Each trial included three 7-min bouts at 60%, 70% and
42 80% of the gas exchange threshold. EE was calculated with four equations by Péronnet
43 & Massicotte, Lusk, Brouwer and Garby & Astrup. **Results:** All four EE equations
44 produced GE estimates that differed from each other (all $P < 0.001$). Reliability
45 parameters were only affected when the typical error was expressed in absolute GE
46 units, suggesting a negligible effect—related to the magnitude of GE produced by each
47 EE equation. The mean coefficient of variation for GE across different exercise
48 intensities and calculation methods was 4.2%. **Conclusions:** Although changing the EE
49 equation does not affect GE reliability, exercise scientists and coaches should be aware
50 that different EE equations produce different GE estimates. Researchers are advised to
51 share their raw data to allow for GE recalculation, enabling comparison between
52 previous and future studies.

53

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

56 **Introduction**

57 Cycling efficiency describes the relationship between mechanical power output and
58 metabolic power input, and it is a determinant of endurance performance¹. Hence, gross
59 efficiency (GE), the most valid index of cycling efficiency¹, can be expressed by:

$$60 \text{ GE (\%)} = [\text{mechanical power output (J}\cdot\text{s}^{-1})/\text{metabolic power input (J}\cdot\text{s}^{-1})] \cdot 100 \quad (1)$$

61
62
63 Different work rate units can be directly converted to J·s⁻¹. In contrast, the metabolic
64 power input, which represents a rate of energy expenditure (EE), can be estimated from
65 several methods. In the cycling efficiency literature, four main equations that calculate
66 EE from gas exchanges under steady-state conditions (see methods) have been used²⁻⁵.

67
68 Recently, Kipp et al.⁶ compared ten published equations when calculating the EE of
69 running bouts. The equation by Péronnet & Massicotte⁷ produced the highest EE
70 estimates⁶. Accordingly, Kipp et al.⁶ recommended that researchers use Péronnet &
71 Massicotte⁷ for its meticulous account of the energy provided from glucose and fat
72 oxidation, based on the latest chemical and physical data available at their time.
73 However, the extent to which different EE equations affect GE in cycling is unknown,
74 suggesting further investigation on this topic is necessary.

75
76 While the inverse relationship between EE and GE is evident, it is less clear whether
77 using different EE equations would affect GE reliability. Yet, differences in
78 measurement ‘noise’ associated with each EE equation would make cycling efficiency
79 studies hard to compare—increasing uncertainty levels, even if the magnitude of GE is
80 minimally impacted.

81
82 We tested the hypothesis that GE estimates and their reliability would be affected by EE
83 equation choice.

84

85 **Methods**

86 **Participants**

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

92

93 **Design**

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

99

100 **Ramp test**

101 The test started with a 10-min warmup at 100 W for men, and 50 W for women.
102 Subsequently, work rate increased continuously at 25 W·min⁻¹ until voluntary
103 exhaustion, or participants’ inability to maintain cadence above 70 rev·min⁻¹. $\dot{V}O_{2\max}$
104 was calculated as the highest 30-s mean, and PPO as the mean power output of the last
105 minute. Gas exchange threshold (GET) was calculated according to the procedures

106 described by Lansley et al. ⁸, as the first disproportionate increase in carbon dioxide
107 output ($\dot{V}CO_2$) vs. oxygen uptake ($\dot{V}O_2$); an increase in ventilatory equivalent for
108 oxygen, with no increase in ventilatory equivalent for carbon dioxide; and an increase in
109 end-tidal oxygen tension with no fall in end-tidal carbon dioxide tension. Two-thirds of
110 the ramp rate was deducted from the work rate at GET to account for the $\dot{V}O_2$ mean
111 response time.

112

113 **Submaximal trials**

114 Participants performed three 7-min bouts consecutively at 60%GET, 70%GET, and
115 80%GET ($34 \pm 4\%$, $39 \pm 5\%$, and $45 \pm 5\%$ PPO). Cyclists were required to report their
116 preferred cadence and hold it constant throughout the study ($86 \pm 6 \text{ rev}\cdot\text{min}^{-1}$). During
117 the last 60 s of each bout, ratings of perceived exertion (RPE) and blood lactate
118 concentration ([La]) were measured. GE was calculated from the mean gas exchanges
119 ($L\cdot\text{min}^{-1}$) in the last 3 min of each 7-min bout according to Equation 1. All participants
120 fulfilled the criteria of a respiratory exchange ratio (RER) ≤ 1.0 in all trials. EE ($J\cdot s^{-1}$)
121 was estimated assuming negligible protein oxidation, according to:

122

123 Péronnet & Massicotte ⁷:

$$124 \text{EE} = 281.67\dot{V}O_2 + 80.65\dot{V}CO_2 \quad (2)$$

125

126 Lusk ⁹:

$$127 \text{EE} = 266.16\dot{V}O_2 + 85.95\dot{V}CO_2 \quad (3)$$

128

129 Brouwer ¹⁰:

$$130 \text{EE} = 269.93\dot{V}O_2 + 83.37\dot{V}CO_2 \quad (4)$$

131

132 Garby & Astrup ¹¹:

$$133 \text{EE} = 267.33\dot{V}O_2 + 82.33\dot{V}CO_2 \quad (5)$$

134

135 **Equipment**

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

141

142 **Statistical analysis**

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

153

154 **Results**

155 There was an interaction between equation and trial for GE at 70%GET ($F = 3.49$; $P =$
156 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
157 ($F = 2.44$; $P = 0.099$; $\eta^2_p = 0.16$). No interactions were found for EE (all intensities $F <$
158 2.56 ; $P > 0.077$; $\eta^2_p < 0.20$).

159
160 There was a main effect of equation for both GE (all intensities $F > 1659.87$; $P < 0.001$;
161 $\eta^2_p > 0.99$) and EE (all intensities $F > 203.46$; $P < 0.001$; $\eta^2_p > 0.94$). All pairwise
162 comparisons were different from each other for both GE (all $P < 0.001$) and EE (all $P <$
163 0.001).

164
165 A main effect of trial was found at 70%GET for both GE ($F = 3.76$; $P = 0.030$; $\eta^2_p =$
166 0.22) and EE ($F = 3.34$; $P = 0.048$; $\eta^2_p = 0.20$). Bonferroni pairwise comparisons
167 revealed that trial 1 was different from trials 2 and 3 (all $P < 0.047$) for GE, and
168 different from trial 2 for EE ($P = 0.037$). At 60%GET and 80%GET, there was no main
169 effect of trial for both GE and EE (all $F < 2.98$; $P > 0.064$; $\eta^2_p < 0.19$).

170

171 [Figure 1]

172

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

175

176 Reliability parameters are presented in Table 1. RPE and [La] in each trial are presented
177 in Table 2. A main effect of trial was found at 70%GET for both RPE ($F = 2.91$; $P =$
178 0.045 ; $\eta^2_p = 0.16$) and [La] ($F = 3.69$; $P = 0.045$; $\eta^2_p = 0.20$). Bonferroni pairwise
179 comparisons revealed that trial 3 was different from trial 4, but for [La] only ($P =$
180 0.037). At 60%GET and 80%GET, there was no main effect of trial for both RPE and
181 [La] (all $F < 2.09$; $P > 0.115$; $\eta^2_p < 0.12$).

182

183 [Table 1]

184 [Table 2]

185

186 Discussion

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

194

195 To illustrate the impact of EE equation on GE, assume a cyclist exercising at a
196 metabolic rate of $1000 \text{ J}\cdot\text{s}^{-1}$, and negligible contribution from the anaerobic metabolism
197 to ATP turnover. Considering the mean GE we found at 80%GET (i.e. 20.6% ⁷, 21.2%
198 ⁹, 21.1% ¹⁰, and 21.4% ¹¹), the cyclist would produce 206, 212, 211, and 214 W,
199 respectively. Clearly, the EE equation choice is important to modelling endurance
200 cycling performance. Our results also suggest GE calculations must be standardised to
201 allow comparability between cycling efficiency studies. We therefore reinforce the
202 recommendations of Kipp et al. ⁶ that researchers abandon outdated equations with
203 incorrect assumptions. Moreover, the raw data from previous and future studies should
204 be provided, allowing for GE recalculation even if new equations are devised.

205

206 GE is recognised as an endurance performance determinant ¹. However, less scientific
207 efforts have been directed toward understanding how to improve GE in comparison to
208 $\dot{V}O_{2max}$ and lactate/ventilatory thresholds. One possible reason may be the lack of
209 standard procedures to measure GE, which confounds the interpretation of published
210 literature. Accordingly, this report should be viewed as an extension of the guidelines
211 proposed by our group ¹, given the choice for the EE equation was not discussed in that
212 work. As the analysis of GE produced some significant differences where EE did not,
213 we also recommend that GE is used in cycling-based studies rather than EE or
214 metabolic rates to express cycling economy. GE takes into account power output,
215 producing a more sensitive measure particularly when researchers adopt relative
216 exercise intensities.

217

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

225

226 **Practical Applications**

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

233

234 **Conclusions**

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

237

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243

244 **References**

245

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284

285 **Figure Captions**

286

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