Gross Efficiency in Cyclic Sports
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Factors affecting gross efficiency in cycling

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Factors affecting gross efficiency in cycling. 


Abstract

There is little standardization of how to measure cycling gross efficiency (GE). Therefore, the purposes of these studies were to evaluate the effect of: 1) stage duration, 2) relative exercise intensity, 3) work capacity, and 4) a prior maximal incremental exercise test on GE. Trained subjects (n = 28) performed incremental tests with stage durations of 1 min, 3 min, and 6 min to establish the effect of stage duration and relative exercise intensity on GE. The effect of work capacity was evaluated by correlating GE with peak power output (PPO). In different subjects (n = 9), GE was measured at 50% PPO with and without a prior maximal incremental exercise test. GE was similar in 3 min and 6 min stages (19.7 ± 2.8% and 19.3 ± 2.0%), but was significantly higher during 1 min stages (21.1 ± 2.7%), GE increased with relative exercise intensity, up to 50% PPO or the power output corresponding to the ventilatory threshold and then remained stable. No relationship between work capacity and GE was found. Prior maximal exercise had a small effect on GE measures; GE was lower after maximal exercise. In conclusion, GE can be determined robustly so long as steady state exercise is performed and RER ≤ 1.0.
Factors affecting gross efficiency in cycling

Chapter 2

Introduction

Exercise performance in endurance sports is broadly understood in terms of the “Joyner model”,1–3 in which performance velocity is a function of the maximal aerobic capacity (e.g. maximal oxygen uptake (\(\text{VO}_{2\text{max}}\))),4,5 \(\text{VO}_{2}\) at the lactate threshold,4,6 and the efficiency with which metabolic energy is transferred into effective power output (PO).7–10 During relatively short competitive events (less than ~10 min) there is also an anaerobic contribution to energy expenditure, which needs to be accounted for.3,11,12 For example, Foster et al.13 found that the relative contribution of anaerobic energy expenditure to total work done during a 3000 m time trial was 30%. In the Joyner model,1–3 there has been a large historical emphasis on \(\text{VO}_{2\text{max}}\) and the ‘fractional utilization’ of \(\text{VO}_{2\text{max}}\). However, more recent studies have recognized that differences in efficiency are often of substantial importance.8–10,14–17

Despite the potential importance of efficiency to physical performance, there is little standardization of how it should be measured and which definition of efficiency should be used. In recent reviews on cycling efficiency by Ettema and Lorås18 and Hopker et al.19 and an earlier review by van Ingen Schenau and Cavanagh20 it was concluded that for whole body movements, definitions of efficiency involving baseline subtractions result in invalid measures of efficiency. The calculation of net efficiency and work efficiency requires estimates of resting metabolism and metabolism during unloaded cycling as a baseline respectively,21 while it is unlikely that these estimates are independent of workload.22 In the definition of delta efficiency the implicit assumption is made that efficiency is independent of workload, although this assumption has been challenged.18 For whole body exercise, like cycling, as used in this study, the only possible definition of efficiency is gross efficiency (GE) (e.g. mechanical PO/metabolic power input (PI)).20 While it is generally thought that efficiency should be based on the measurement of steady state oxygen uptake (\(\text{VO}_{2}\)), some studies have reported efficiency results from incremental protocols with fairly short stage durations, where \(\text{VO}_{2}\) kinetics may prevent attaining the steady state conditions. For the above stated definition of GE, in which the metabolic PI is only based on aerobic metabolism, \(\text{VO}_{2}\) needs to be in steady state, because otherwise there may be an unmeasured anaerobic component to energy production, which has not been taken into account. However, as athletes are often tested using an incremental test with short stage duration, it would be interesting to evaluate the effect of a short stage duration, where steady state is not yet obtained, on GE. Ettema and Lorås18 showed in their review that GE increases with absolute exercise intensity, but it might be better to
determine GE at a relative exercise intensity. However, there are few data demonstrating the effect of either stage duration or relative exercise intensity on GE.

The highest reported GE values are typically observed in elite cyclists.\textsuperscript{10,18} It is unclear, however, whether this represents an effect of work capacity (e.g. peak power output (PPO)), training or simply selection for high efficiency amongst competitive cyclists. Therefore, the effect of PPO on GE needs to be evaluated.

Finally, given that measures of efficiency are ideally based on a PO that is relative to the individual maximal value, the effect of measuring efficiency during a single exercise session, following a maximal incremental test, versus in a separate session, is of interest. Passfield and Doust\textsuperscript{23} showed that GE decreases during a 60 min exercise bout at 60% $\dot{V}O_{2\text{max}}$, which suggests that when GE is determined after a maximal incremental test, this would result in a lower GE. Summarizing, the purposes of this study were to evaluate the effect of stage duration, relative exercise intensity, work capacity, and prior maximal incremental exercise on GE.

**Methods**

The study was conducted in two independent parts, *Study 1* and *Study 2*. Subject characteristics of *Study 1* and 2 are summarized in Table 2.1. Prior to the first test all subjects provided written informed consent, and the protocol was approved by the local ethics committees and meets the ethical standards of the International Journal of Sports Medicine.\textsuperscript{24} All subjects were healthy and physically active, including both competitive athletes and fit non-athletes. In all studies the subjects first performed a maximal incremental exercise test on a custom made electronically braked cycle ergometer (VU-MTO, Amsterdam, The Netherlands) in *Study 1*, or on a commercial electronically braked cycle ergometer (Excalibur Sport, Lode Medical Technology, Groningen, The Netherlands) in *Study 2*. Maximal incremental exercise tests started with a warm-up of 3 min at 25 W, after which PO was increased by 25 W·min\textsuperscript{-1} till fatigue. Pedaling frequency was kept constant at 80 revolutions per minute by visual feedback from the ergometer. Gas exchange data were measured using open circuit spirometry. In *Study 1* breath-by-breath measurements of oxygen uptake (Cosmed Quark b\textsuperscript{2}, Cosmed S. R. L., Rome, Italy) were averaged over 30 s intervals. In *Study 2* a metabolic cart with a mixing chamber was used (AEI, Pittsburgh, PA, USA) and gas exchange data was integrated every 30 s. In both studies the gas analyzers were calibrated with gas mixtures of known composition and the volume transducer was calibrated using a 3 L volume syringe. Ventilatory (VT) and Respiratory Compensation (RCT) thresholds were identified using both the ‘V-slope’\textsuperscript{25}
Factors affecting gross efficiency in cycling

and ventilatory equivalent methods. GE was calculated according to Garby and Astrup (see below). Heart rate (HR) was measured using radiotelemetry (Polar Avantage, Polar Electro OY, Kempele, Finland), and the Rating of Perceived Exertion (RPE) was measured using the Category Ratio (0-10) RPE scale.

<table>
<thead>
<tr>
<th>Study 1</th>
<th>Males (n = 16)</th>
<th>Females (n = 12)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yr)</td>
<td>23.9 ± 6.1</td>
<td>30.0 ± 7.2</td>
</tr>
<tr>
<td>Body mass (kg)</td>
<td>78.4 ± 9.9</td>
<td>59.2 ± 7.6</td>
</tr>
<tr>
<td>$\dot{V}O_2$ (L·min$^{-1}$)</td>
<td>4.80 ± 0.60</td>
<td>3.02 ± 0.40</td>
</tr>
<tr>
<td>$\dot{V}O_2@VT$ (L·min$^{-1}$)</td>
<td>2.50 ± 0.56</td>
<td>1.88 ± 0.29</td>
</tr>
<tr>
<td>PPO (W)</td>
<td>357 ± 62</td>
<td>267 ± 29</td>
</tr>
<tr>
<td>PPO (W·kg$^{-1}$)</td>
<td>4.55 ± 0.50</td>
<td>4.51 ± 0.40</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Study 2</th>
<th>Males (n = 5)</th>
<th>Females (n = 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yr)</td>
<td>28.4 ± 17.1</td>
<td>21.5 ± 4.1</td>
</tr>
<tr>
<td>Body Mass (kg)</td>
<td>79.5 ± 19.2</td>
<td>66.4 ± 7.4</td>
</tr>
<tr>
<td>$\dot{V}O_2$ (L·min$^{-1}$)</td>
<td>3.33 ± 0.35</td>
<td>2.33 ± 0.59</td>
</tr>
<tr>
<td>$\dot{V}O_2@VT$ (L·min$^{-1}$)</td>
<td>2.00 ± 0.29</td>
<td>1.50 ± 0.17</td>
</tr>
<tr>
<td>PPO (W)</td>
<td>255 ± 33</td>
<td>196 ± 27</td>
</tr>
<tr>
<td>PPO (W·kg$^{-1}$)</td>
<td>3.21 ± 0.44</td>
<td>2.95 ± 0.35</td>
</tr>
</tbody>
</table>

Values are reported as means ± standard deviations. $\dot{V}O_2$, maximal oxygen uptake; $\dot{V}O_2@VT$, oxygen uptake at the ventilatory threshold; PPO, peak power output.

To study the effect of stage duration on GE in Study 1, each subject performed, on separate days, incremental exercise tests, with increments in PO of 25 W every 1 min, 3 min or 6 min, following a warm-up of 3 min at 25 W. All subjects started with the 1 min protocol, but the order of the 3 min and 6 min stage durations was randomized. The 1 min and 3 min protocols were continued until exhaustion, and the 6 min protocol was discontinued when the respiratory exchange ratio (RER) exceeded 1.0. Average $\dot{V}O_2$ and RER values were determined over the last 30 s of each stage and GE was calculated using Equations 2.1 and 2.2:

\[
GE = \frac{PO}{PI} \cdot 100 \quad \text{Equation 2.1}
\]

\[
PI = \dot{V}O_2 \cdot (4940 \cdot RER + 16040) \quad \text{Equation 2.2}
\]
\( \dot{V}O_2 \) in equation 2.2 is expressed in L·s\(^{-1}\). GE was only calculated for stages where the average RER \( \leq 1.0 \). GE can only be determined validly on the basis of oxygen consumption when \( \dot{V}O_2 \) is in steady state,\(^{29}\) which takes about 2-3 min. However to study the effect of a short stage duration on the error in GE, the same calculation was applied to the 1 min stages. The absolute and \% difference in average \( \dot{V}O_2 \) between the last and second last 30 s was determined to study steady state conditions. Besides that, the average \( \dot{V}O_2 \) for both intervals was compared using a repeated measures ANOVA, with two within subject factors, i.e. PO and interval (for last and last 30 s). For analytic purposes, only data from exercise stages (e.g. 50-150 W) without missing values of any of the subjects were included to test the effect of stage duration. The effect of stage duration and absolute PO on GE was evaluated using a repeated measures ANOVA (PASW 18.0, SPSS Inc., Chicago, IL, USA) with two within subject factors. If the assumption of sphericity was violated, the Greenhouse Geisser correction was applied to the degrees of freedom, and post hoc pair-wise comparisons were tested using the Bonferroni method.

To evaluate the effect of relative exercise intensity on GE, the data from all stages during the 3 min and 6 min protocols were included as long as RER \( \leq 1.0 \). The data were pooled, and plotted relative to \% PPO, and \% PO at VT (% PO\(_{VT}\)) achieved during the 1 min stage test. The data were fitted with a least squares polynomial curve to achieve the highest \( R^2 \). Statistical comparisons were made using multiple regression by testing the significance of the increase in \( R^2 \) from adding a more complex polynomial curve.

The relation between work capacity and GE, determined at 50\% PPO, was studied using linear regression analysis. Although multiple definitions of work capacity could be used, PPO was used as the simplest expression, particularly since very high GE values have often been observed in individuals with high PPO values.\(^{10}\)

In Study 2 all subjects exercised in the laboratory on 2 separate days (~7 days apart). On the first day, each subject performed a maximal incremental exercise test using the 1 min protocol, as was done in Study 1. At the end of the test, PO was decreased to 25 W and subjects continued pedaling for 10 min. After this recovery period, PO was increased to 50\% PPO and maintained for 10 min. GE was calculated using average \( \dot{V}O_2 \) and RER values during the final 60 s of this period, with the requirement that RER \( \leq 1.0 \). On the second day, the subject warmed-up by following the incremental protocol until 50\% PPO was achieved and continued at this PO for 10 min. Again GE was calculated during the final 60 s of this period with the requirement that RER \( \leq 1.0 \). Differences in \( \dot{V}O_2 \), HR, RPE, and GE between the condition with and without a prior maximal incremental exercise test were analyzed using a paired samples t-test.\(^{30}\) The effect of prior maximal exercise on GE was also evaluated using a standardized Cohen’s effect size measure.\(^{30}\)
Results

The effect of stage duration on GE is presented in Figure 2.1. A significant main effect of both PO ($F = 499.3$, $p < 0.001$) and stage duration ($F = 8.36$, $p < 0.01$) on GE was found. Post hoc pair-wise comparisons revealed that all POs differed significantly from one another ($p < 0.001$, observed power 1.0 computed using $\alpha = 0.05$). Post hoc comparisons between the different stage durations revealed that the test with 1 min stages resulted in significantly higher calculated GE values compared with the 3 min and 6 min tests (mean difference $1.8\%$ and 95% confidence interval (CI) 0.3-3.3%, $p < 0.05$, and mean difference $1.7\%$ and 95% CI 0.4-3.0%, $p < 0.01$, respectively). The 3 min and 6 min tests did not result in significantly different GE values (mean difference $-0.1\%$ and 95% CI -1.0-0.8%, observed power 0.79). No significant interaction effect between stage duration and PO was found ($F = 0.98$, $p = 0.41$). At matched POs, GE during the 1 min protocol was systematically higher (~2%) than during the 3 min and 6 min protocols, with a relatively constant difference. The difference in GE between the 1 min protocol and the 3 min and 6 min protocols was larger for subjects with higher GE values (Figure 2.2).

Calculating the difference in average $\dot{V}O_2$ between the last and second last 30 s intervals resulted in the finding that the 1 min protocol, as expected, did not result in steady state conditions. The absolute difference between the last and second last 30 s interval was $152.40 \pm 96.35$ mL·min$^{-1}$, which corresponded to a difference of $8.81 \pm 5.44\%$. Besides that, there was a significant difference in average $\dot{V}O_2$ between the last and second last 30 s interval for all POs combined ($F = 114.6$, $p < 0.001$). No significant interaction effect between PO and interval (for last and last 30 s) was found. The 3 min and 6 min protocol resulted in an average absolute difference between the last and for last 30 s interval of $5.93 \pm 65.20$ mL·min$^{-1}$ and $-15.42 \pm 62.90$ mL·min$^{-1}$, which corresponds to a difference of $0.22 \pm 3.55\%$ and $-0.77 \pm 3.32\%$, respectively. No significant difference in average $\dot{V}O_2$ between the last and second last 30 s interval was found for the 3 min and 6 min stages ($F = 0.45$, $p = 0.51$; $F = 0.95$, $p = 0.34$).

The effect of % PPO and % POVT on GE is presented in Figure 2.3. GE increased until ~50% PPO and ~100% POVT and then remained constant to the limit of the measured values (Figure 2.3A and B). Coincidently, ~50% PPO corresponded to ~100% POVT (Figure 2.3C). Figure 2.3D shows that there was no systematic relationship between work capacity (PPO) and GE determined at 50% PPO ($r^2 = 0.03$).
Gross efficiency in cyclic sports

Figure 2.1 The average gross efficiency (GE) as determined during stages of 1 min, 3 min, and 6 min. To improve the clarity of the figure, no error bars are displayed.

Figure 2.2 Relationship between gross efficiency (GE) determined during stages of 1 min vs. GE determined during stages of 3 min and 6 min in duration. The dashed line is the line of identity and the solid line represents the relationship between the 1 min GE values and the 3 min and 6 min GE values.
Factors affecting gross efficiency in cycling

Chapter 2

Figure 2.3 The effect of relative exercise intensity (A and B) and work capacity (D) on GE. A: Relationship between percent peak power output (% PPO) obtained during a 1 min stage maximal incremental test and gross efficiency (GE) determined during 3 min and 6 min stages. GE increases until approximately 50% PPO, and then remains relatively constant up to the limits of measurement. B: Relationship between percent power output at the ventilatory threshold (% POVT) and GE determined during the 3 min and 6 min stages. GE increases until approximately 100% POVT and then remains relatively unchanged up to the limits of measurement. C: Relationship between % PPO obtained during a 1 min stage incremental exercise test and % POVT during the same exercise test. D: Relationship between work capacity, determined as PPO during a 1 min incremental exercise test and GE determined at 50% PPO during a 3 min and 6 min stage. There was no overall relationship between work capacity and GE (r = 0.18, NS).

The results of Study 2 are presented in Figure 2.4. The difference in GE between the with and without prior maximal incremental exercise test condition was not significant (17.4 ± 2.0% vs. 18.1 ± 1.8%, t = -2.12, p = 0.067). The percentage difference, calculated after log-transformation, was 4.5% and Cohen’s effect size was 0.36, which is a small effect. \( \text{VO}_2 \) was significantly lower in the without as compared to the with prior maximal incremental exercise test condition (1.81 ± 0.27 L·min\(^{-1}\) vs. 1.93 ± 0.30 L·min\(^{-1}\), t = 3.02, p < 0.05). HR was also significantly lower in the without prior maximal incremental exercise test condition (140 ± 20 beats·min\(^{-1}\) vs. 147 ± 19 beats·min\(^{-1}\)) (t = 2.91, p < 0.05). No significant difference in RPE was found between conditions (4.0 ± 0.7 vs. 4.7 ± 1.7, t = 1.51, p = 0.169).
Figure 2.4 Relationship between gross efficiency (GE) determined during a 10 min submaximal exercise bout without a prior maximal incremental exercise test and during a 10 min submaximal exercise test performed following a maximal incremental exercise test. A small effect of prior maximal exercise was found on GE. The dashed line represents the line of identity and the solid line represents the relationship between GE determined with and without a prior maximal incremental exercise test.

Discussion

The main findings of this study were that: 1) GE was significantly higher during short stage duration (1 min) exercise compared to 3 min and 6 min stage durations; 2) GE increased until about 50% PPO, which corresponded to the intensity associated with VT, and then remained stable up to the limits of the ability to measure GE (RER ≤ 1.0); 3) there was no systematic relationship between work capacity, expressed as PPO, and GE and 4) GE values obtained following a brief (10 min) recovery period after a maximal incremental exercise test were not statistically different (α = 0.05) from those obtained in a standalone submaximal exercise test designed to measure GE, but using standardized Cohen’s effect size a small effect was found.

The difference found in GE between the 1 min, 3 min, and 6 min stage durations is due to non steady state conditions for the 1 min stage durations, as it usually takes 2-3 min for trained subjects to reach steady state,\textsuperscript{31} which was confirmed by the data of this study.
The difference seems to be relatively constant in the range of a ~2% higher GE, although clearly individual differences exist (Figure 2.2), particularly for individuals with higher values for GE. In the literature, attempts to include the anaerobic work to PI have been undertaken using blood lactate values obtained after the submaximal exercise bouts. However, di Prampero and Ferretti commented in their review that it is only correct to assume a continuous anaerobic lactic contribution to exercise when lactate keeps increasing during exercise. So, attempts to include the anaerobic work that are based on lactate values obtained only after exercise, are probably not entirely defensible. On this basis, studies which attempt to determine GE on the basis of VO₂ responses during rapidly incremented protocols should be discouraged.

The results of evaluating the effect of exercise intensity on GE are in agreement with the findings of Ettema and Lorås. Based on a review of the available literature on the effect of cadence and work rate on cycling efficiency, these authors found that GE increased in a curvilinear manner with increasing PO and that this effect diminishes when PO increases above 150 W. When GE was plotted against relative exercise intensity, GE reached a plateau around 50% PPO, which coincidently corresponded to 100% POVT. The tendency to reach near constant GE values at an exercise intensity approximately equivalent to VT undoubtedly represents the combined effect of a decreasing relative importance of a constant resting VO₂ and the inability to make measurements of GE when RER >1.0.

Our hypothesis that the highest GE values would be found in subjects with the highest PPO, reached during a maximal incremental exercise test, was not supported by the data. No significant relationship between PPO and GE was found, which implies that subjects with a high PPO are not necessarily efficient.

The results of Study 2 showed that GE values obtained following a brief (10 min) recovery period after a maximal incremental exercise test were not statistically different from those obtained in a standalone submaximal exercise test. However, a small effect was found using Cohen’s effect size, which suggests that the GE values are different. Besides that, the difference of 4.5% between conditions is a meaningful difference for athletes. Sahlin et al. investigated the effect of prior heavy exercise, causing pronounced acidosis, on VO₂ kinetics. GE was determined (at min 3 and min 10) during 10 min cycling at 75% VO₂peak, before and after heavy exercise. GE was 12% lower at 3 min and 5% lower at 10 min, when preceded by a heavy exercise bout as compared to the control condition. Thus, Sahlin et al. found a significantly lower GE after heavy exercise, which supports our effect size results. Burnley et al. studied the effect of recovery time following heavy exercise on VO₂ kinetics. Heavy exercise resulted in an increase in the
primary \( \dot{V}O_2 \) amplitude when a second heavy exercise bout was performed after 10 min of passive recovery. This increase in primary \( \dot{V}O_2 \) amplitude was still present after 45 min of recovery, but was absent after 60 min of recovery. It is therefore most likely that prior heavy exercise, like a maximal incremental exercise test, would result in a decrease in GE, which may last up to 45 min, although additional research is required to confirm this hypothesis.

In summary, GE determined during incremental cycling exercise seems to be dependent on stage duration, reaches constant values in the range of 50% PPO or 100% PO\textsubscript{VT}, is independent of work capacity, and finally more research is required to evaluate the effect of recovery duration on GE measurements after a maximal incremental exercise test.
References


