No Differences in Cycling Efficiency Between World-Class and Recreational Cyclists

Abstract

The aim of this experiment was to compare the efficiency of elite cyclists with that of trained and recreational cyclists. Male subjects (N = 69) performed an incremental exercise test to exhaustion on an electrically braked cycle ergometer. Cadence was maintained between 80–90 rpm. Energy expenditure was estimated from measures of oxygen uptake ($V_{\text{O}_2}$) and carbon dioxide production ($V_{\text{CO}_2}$) using stoichiometric equations. Subjects (age 26 ± 7 yr, body mass 74.0 ± 6.3 kg, $W_{\text{peak}}$ 359 ± 40 W and $V_{\text{O}_2,\text{peak}}$ 2.3 ± 0.7 mL/kg/min) were divided into 3 groups on the basis of their $V_{\text{O}_2,\text{peak}}$ (< 60.0 (Low, N = 26), 60–70 (Med, N = 27) and > 70 (High, N = 16) mL/kg/min). All data are mean ± SE. Despite the wide range in aerobic capacities, gross efficiency ($GE_{165}$) at 165 W ($GE_{165}$), $GE_{165}$ at the same relative intensity ($GE_{\text{rel}}$), delta efficiency ($DE$) and economy ($EC$) were similar between all groups. Mean $GE_{165}$ was 18.6 ± 0.3%, 18.8 ± 0.4% and 17.9 ± 0.3% while mean $DE$ was 22.4 ± 0.4%, 21.6 ± 0.4% and 21.2 ± 0.5% (for Low, Medium and High, respectively). There was no correlation between $GE_{165}$, $GE_{\text{rel}}$, $DE$ or $EC$ and $V_{\text{O}_2,\text{peak}}$. Based on these data, we conclude that there are no differences in efficiency and economy between elite cyclists and recreational level cyclists.

Keywords

Gross efficiency • delta efficiency • economy • $V_{\text{O}_2,\text{peak}}$

Introduction

Metabolic efficiency is the ratio of the total amount of the effective mechanical work done by the muscles and energy expended by the body [10]. Metabolic efficiency during cycling (cycling efficiency) has been reported to range from 18 to 23% [8] and an improvement in efficiency implies an increase in mechanical power output for any specific metabolic cost. The 18–23% range suggests that, for the same rate of metabolic energy expenditure, a highly efficient individual could produce 28% more power than an individual with low efficiency (i.e., 23%–18%)/(18%–28%). Indeed, the importance of cycling efficiency has been recognized by previous investigators [5,6,13,23,25]. Horowitz et al. (1994) suggested that a 1.8% difference in gross efficiency ($GE$) could result in a 10% difference in maximal sustained power during a 1-hour cycling performance test [13]. Additionally, mathematical modelling has been used to predict that a 1% change in efficiency could result in a 63 s improvement in 40 km time trial performance [16]. The performance enhancing potential of increasing efficiency has created an interest in the factors influencing cycling efficiency and, furthermore, whether it is possible to alter cycling efficiency.

Previous investigators have reported that several factors, including altitude, fatigue, muscle shortening velocity, fiber type, and temperature affect cycling efficiency. Green et al. [11] reported a serious deterioration in mechanical efficiency at moderate fatigue levels (129%) compared to that at low fatigue levels (12%). At high fatigue levels, mechanical efficiency dropped to 117%. The drop in mechanical efficiency was significant when compared to low fatigue levels. These findings indicate that mechanical efficiency is reduced at high fatigue levels. The drop in mechanical efficiency with fatigue may be due to the decreased muscle force generating capacity or the increased energy demand for maintaining the same mechanical work output.

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Bibliography

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Respondents 60

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Although the factors mentioned above are known to influence ef-
ciciency, has found no relationship between these factors, there
s cycling efficiency (2,21,24,29). While the greater part of the lit-
ed is increase with pedal speed (a marker for muscle shortening
el). Coyle et al. found a positive correlation between
el response and pedalling rate (rpm) using different
k lengths and cadences and reported that delta efficiency
DE) increased with pedal speed (a marker for muscle shortening
el) [22]. Coyle et al. found a positive correlation between
el efficiency was not calculated [19]. In a later study an inverse rela-
cy was reported [18]. However the data suggest exceptionally
ially high values for efficiency and have recently been questioned
[15]. The idea of a link between aerobic capacity and cycling effi-
cy is an appealing one as it is theoretically possible that
training improves efficiency. It is certainly well known that train-
ing can modify the physiology and biochemistry of humans [27]
and it seems possible that such plasticity may extend to meta-
bolic efficiency, perhaps through changes in fiber type, muscle
recruitment pattern or via the expression of different uncoupling
proteins. Additionally, the importance of efficiency on performance
would suggest that having high cycling efficiency would be a prerequisite for competitive success. In this mind, and
in light of the recently published data of Lucia et al. [2002 [18],
the purpose of this study was to determine whether cycling effi-
cy was different in cyclists of different abilities. To accomplish
this purpose, we used a cross-sectional design and recruited a subject population that varied widely in aerobic ca-

### Methods

Sixty-nine male cyclists participated in this study. The subjects
in this study ranged from those who were recreational cyclists
to those who were world-class professional road racing cyclists
(e.g. ranked in the top 200 in the world according to the inter-
national governing body for cycling, the Union Cycliste Interna-
tionale (UCI) [14]). The study was reviewed and approved by the
ethics committee within the University of Birmingham, and all
subjects gave their written informed consent after reading the
information and the procedure having been explained to them.
The subjects were divided into three groups on the basis of their
peak oxygen uptake (VO_2peak), the criteria being <50 mL/kg/min
(Low, N = 26), 50-70 mL/kg/min (Med, N = 27) and >70 mL/kg/min
(High, N = 16). Group characteristics are shown in Table 1. Indi-
individual values of VO_2peak ranged from 3.41 to 6.39 L/min and
the overall mean was 4.97 ± 0.68 L/min.

All subjects performed an identical graded exercise test to ex-
haustion on an electrically braked cycle ergometer (Lode Excali-
bur Sport, Lode, Groningen, The Netherlands). Measures of VO_2,
VCO_2 and mechanical power output were made throughout the
exercise test. Energy expenditure was calculated using stoichio-
metric equations [3] and, in conjunction with workload (power output), GE, DE and economy (EC) were calculated.

After a minimum three hour fast, subjects arrived at the lab
where we measured and recorded weight and height. The sub-
jects' position on the ergometer was adjusted to match their ac-
custom riding position. Subjects could use their own pedal
binding systems or subjects' feet were securely fastened to the
pedals. The graded exercise test began with a power of 95 W
and power was increased by 35 W every three minutes. Excep-
tions to this were nine subjects for whom the test began at
165 W. Subjects were asked to maintain their cadence at be-
tween 80-90 rpm and were given visual feedback from the Lode
del control box in order to do this. Once the RER rose consistently
above 1.00 for an entire workload, the measures of energy expend-
iture were no longer valid and maintenance of cadence was no
longer necessary but exercise was continued to exhaustion in or-
der to determine VO_2peak and Wpeak. VO_2peak was defined as
the highest oxygen uptake value observed during the incremen-
tal exercise test to exhaustion while Wpeak was calculated as the
last completed work rate, plus the fraction of time spent in the
final non-completed work rate multiplied by the work rate incre-
ment. Subjects were asked to refrain from strenuous exercise the
day preceding each test. Dietary composition on the day prior to
the test was not recorded. Subjects were asked to ensure a diet

### Table 1 Summary of subject characteristics

<table>
<thead>
<tr>
<th>Group</th>
<th>N</th>
<th>Age (years)</th>
<th>Body mass (kg)</th>
<th>Height (cm)</th>
<th>VO_2peak (mL/kg/min)</th>
<th>VO_2peak (L/min)</th>
<th>Wpeak (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>26</td>
<td>77.3 ± 1.8</td>
<td>75.2 ± 1.2</td>
<td>180 ± 1</td>
<td>56.1 ± 0.8*</td>
<td>4.20 ± 0.05*</td>
<td>339 ± 6</td>
</tr>
<tr>
<td>Med</td>
<td>27</td>
<td>24.0 ± 1.1</td>
<td>73.5 ± 1.4</td>
<td>181 ± 1</td>
<td>64.2 ± 0.5*</td>
<td>4.72 ± 0.08*</td>
<td>366 ± 7</td>
</tr>
<tr>
<td>High</td>
<td>16</td>
<td>25.5 ± 1.4</td>
<td>70.9 ± 1.6</td>
<td>182 ± 2</td>
<td>75.2 ± 1.0*</td>
<td>5.32 ± 0.12*</td>
<td>403 ± 8</td>
</tr>
</tbody>
</table>

All data are mean ± SE. * = significantly different from either 2 groups (p < 0.0001). ++ = significantly different from High (p < 0.0001). +++ = significantly different from Med (p < 0.005). ++ = significantly different from High (p < 0.005)
The gometer was calibrated by measuring reactive torque at the end of the study. The variation in GE with mechanical power was used with a Mann-Whitney U test to identify the position of any differences. The data representing the measures of efficiency and economy are presented in Table 2. There were no significant differences between groups for GE\textsubscript{eq}, GE\textsubscript{eq}, DE or EC. Data illustrating the relationship between GE\textsubscript{eq} (%) and VO\textsubscript{2peak} (mL/kg/min) and W\textsubscript{peak} are shown in Fig. 1. There was no significant relationship between the two variables with the relationship described by the formula y = -0.0348x + 20.752 (R\textsuperscript{2} = 0.0372). In a similar fashion there were no significant correlations between GE\textsubscript{eq}, GE\textsubscript{eq}, DE and VO\textsubscript{2peak} (mL/kg/min or l/min). There was a weak significant correlation (R\textsuperscript{2} = 0.06, p < 0.05) between W\textsubscript{peak} and EC, which is shown in Fig. 2, however EC was not significantly correlated with VO\textsubscript{2peak} (mL/kg/min or l/min). The relationship between GE and mechanical power is illustrated in Fig. 3, with significant increments in GE at the lower work rates (95, 130 and 165 W). There were no further statistically significant increases in GE greater than 165 W.

Results

Group characteristics are shown in Table 1. Groups did not differ in height, weight or age. As expected, the groups differed significantly in VO\textsubscript{2peak} (expressed as both mL/kg/min and l/min) and W\textsubscript{peak}.

Table 2 Summary of group efficiency and economy data. All data are mean ± SE. There are no significant differences between groups (p < 0.05)

<table>
<thead>
<tr>
<th>Group</th>
<th>GE\textsubscript{eq} (%)</th>
<th>GE\textsubscript{eq} (%)</th>
<th>DE (%)</th>
<th>EC (kg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>18.8 ± 0.6</td>
<td>18.6 ± 0.3</td>
<td>22.4 ± 0.4</td>
<td>4.3 ± 0.1</td>
</tr>
<tr>
<td>Med</td>
<td>18.6 ± 0.8</td>
<td>18.2 ± 0.4</td>
<td>21.6 ± 0.4</td>
<td>4.3 ± 0.1</td>
</tr>
<tr>
<td>High</td>
<td>18.9 ± 0.2</td>
<td>17.9 ± 0.3</td>
<td>21.2 ± 0.5</td>
<td>4.2 ± 0.1</td>
</tr>
</tbody>
</table>

The data from each individual were sorted into three groups according to VO\textsubscript{2peak}. The distribution of the data within each variable was assessed using a Shapiro-Wilk test. Normally distributed data was analyzed with a one-way ANOVA. If significant differences were detected a Scheffe post-hoc test was used to determine which groups differed. In the event of the data not being distributed normally a non-parametric Kruskal-Wallis H test was used with a Mann-Whitney U test to identify the position of any differences. The variation in GE with mechanical power for all subjects was assessed using a one-way ANOVA with a Scheffe post-hoc.
Discussion

The most important finding of this study is that there were no differences in measures of cycling efficiency despite the very wide range of aerobic capacities amongst our subject population. This observation supports reports by previous investigators [2,21,24,29] who examined the effects of aerobic capacity/cycling experience on efficiency in cycling. Those investigators, however, did not use as large a range of aerobic capacities as utilized in this case (the largest range being 44.2–71.2 mL/kg/min [21]), or large numbers of participants (maximum N = 31 [21]). We had access to a large group of cyclists who exhibited a wide range of aerobic capacities (N = 69, 45.1–83.1 mL/kg/min) and were able to more thoroughly examine this link. Thus our results confirm and expand upon previous research with a larger range in aerobic capacity and more subjects.

It is important that the potential limitations of this study are acknowledged. Most previous investigators of cycling efficiency have used indirect calorimetry and precisely controlled work rates, and then used those measures to calculate efficiency, just as we did. Even so, it is possible that these methods are not precise enough to accurately determine physiological differences in efficiency between individuals. Recently, however, we reported that the coefficients of variation for GE, DE and EC during cycling were 3.2 (2.4–4.2)%, 5.8 (4.3–8.8)%, and 2.8 (2.1–4.4)%, respectively (mean [confidence limits]) [23]. Assuming GE and DE to be 20% and EC to be 4.3 kJ/L that data would suggest that differences greater than 0.64% in GE, 1.16% in DE and 0.12 kJ/L in EC could be identified using this protocol. In addition, it might be suggested that the use of indirect calorimetry is not valid when using an incremental exercise test with 3-minute stages due to the time taken for VO2 to reach steady state. Data from our laboratory compared VO2 and VC02 data collected in the last 2 minutes of each stage using this protocol with VO2 and VC02 data collected from the same subjects who returned on different days and performed steady state exercise of at least 30 min duration at the same workloads [1]. No significant differences were observed in VO2 and VC02 between the experimental methods, suggesting that this protocol is valid. The final point to discuss when addressing the stage length is that data presented by McDaniel et al. (see Fig. 5 in [22]) indicates that metabolic cost during a 5 minute incremental protocol was stable during minutes 3, 4, and 5 [22]. It is possible that the degree to which an individual hyperventilates at a given absolute/relative intensity differs with their aerobic capacity. Differences in VE could affect the accuracy of the measures of energy expenditure via the relationship between substrate oxidation and VC02. However, given the low relative intensity of the 165 W stage (49 ± 1, 45 ± 1 and 41 ± 1% of Wmax for Low, Med and High respectively) it is unlikely that there will have been a significant effect of VE on GE. In addition, while it is possible that hyperventilation could affect measures of energy expenditure at GE, the relative workload was greater (76 ± 2, 76 ± 3, 80 ± 2% of Wmax for Low, Med and High respectively), the comparable relative intensity sug-


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gests that this would affect each group to a similar degree. Finally, if VCO2 were to significantly lag behind VO2, it could have the potential to invalidate the stoichiometric equations. In order to assess this effect economy was calculated at 165 W and all subjects exhibited economies within 1 SD of the mean (mean ± SD = 4.2 ± 0.3[kJ]).

As mentioned, our results support the findings of previous investigators. Marsh et al. examined the separate effects of maximal aerobic capacity and cycling experience on cycling efficiency [21]. Neither cycling experience nor aerobic capacity significantly affected DE although a non-significant trend for trained cyclists having 1-2% higher DE was observed. Stuart et al. compared the efficiency of sprint runners with low VO2max and distance runners with high VO2max and reported no differences in DE but did report that the sprinters had a significantly lower GE than the endurance runners [29]. Interpretation of these results with respect to aerobic capacity per se is difficult because the lower VO2max group was comprised of highly trained sprinters who are likely to have lower % type I fibers [27] and thus would be expected to be less efficient than those with higher proportion of slow twitch fibres [8]. Nickleberry and Brooks examined the interaction of cycling experience and cycling efficiency by comparing GE and DE in competitive and recreational cyclists using both incremental and steady state submaximal exercise at cadences of 50 and 80 rpm [24]. The authors concluded that previous cycling experience was of minor importance in comparing efficiency. While offering strong evidence for the lesser role of experience in deciding efficiency, the reported VO2peak values for both groups were lower than those normally reported in the literature for competitive and recreational cyclists (48.6 ml/kg/min and 39.8 ml/kg/min respectively) and therefore additional data to extend the findings to a larger group of cyclists was warranted. Boning et al. compared the efficiency of trained cyclists and untrained individuals [2]. Trained cyclists exhibited a small but statistically significant greater GE; however, the authors noted that the untrained subjects exceeded the anaerobic threshold and once the oxygen debt was taken into account the differences in adjusted net efficiency became negligible. Taken together, the results from these studies indicate no clear differences in efficiency between groups that differ in aerobic capacity or cycling experience. Thus our data, collected from subjects within a large range in their VO2peak, are consistent with previous reports utilizing smaller ranges in VO2peak. Our findings, however, do not agree with those of Lucia et al. [18]. This data has been questioned [15], with the gross efficiency data reported by Lucia et al. markedly higher than that reported elsewhere in the literature [5,8,13,23], and our data would tend to support those doubts. Suggested explanations for the findings of Lucia et al. include erroneous VO2 data as well as errors in the calculations [15].

The CUC has been postulated to represent the cost of moving the limbs [28] and is known to increase with pedal speed [22]. The values reported here are of a similar magnitude to those seen elsewhere in the literature [22,29]. The effect of the CUC on GE is largest at low powers, where it represents a considerable proportion of the total metabolic cost, and thus GE appears to increase with increased mechanical power [22]. This increase presents one of the difficulties in comparing the efficiencies of subjects with large variations in their aerobic capacities. Comparisons between groups were therefore made at both the same relative exercise intensity (GEmax, the GE at the last workload before the RER exceeded 1.00) and the same absolute exercise intensity (GEint). Analysis of the overall variation in GE with mechanical power shows that the GE at all powers above 130 W formed a homogeneous subset with no significant differences in GE and therefore GEint is representative of GE at all workloads greater than 130 W. It is known that cadence can affect both CUC and DE [4,8,13,28]. Therefore we asked subjects to adopt cadences within a narrow range (80 and 90 rpm) controlling this variable while ensuring errors due to subjects adopting unnatural cadences were avoided. Recent research has quantified the relationship between pedal speed and CUC and increasing pedaling rate from 80 to 90 rpm would increase the CUC by 32.3 W and DE by 0.12% [22]. In our study, cadence data was not collected and therefore we cannot determine the extent to which pedalling rate may have influenced our results. Even so, a 0.12% change in DE is not great enough for the difference between the Low and High groups to become significant but the trend for a higher CUC in the High group could potentially be explained by an increased cadence in the High group.

The metabolic cost of producing any specific mechanical power output was similar for all groups (Fig. 4). Consequently we expected that the high VO2 group would exhibit greater GE simply because they could reach higher work rates and metabolic energy expenditures at which the effect of CUC should be reduced and GE would tend to approach DE. Even in the High group, however, the decreased effect of CUC did not significantly increase GE compared with the Low group. This result was probably due to the magnitude of the absolute differences in VO2peak of our groups. Specifically, the VO2peak of our Low group was 4.2 L/min and thus, the Medium (4.8 L/min) and High (5.3 L/min) group were only 12 and 27% greater in absolute VO2peak. This difference was reduced at VO2max (Low: 3.4 ± 0.1 L/min [22% lower than High], Medium: 3.8 ± 0.1 L/min [14% lower than High], High: 4.3 ± 0.1 L/min). Thus, the differences in submaximal metabolic cost were not large enough to reach a significant difference in GE based solely on the effect of CUC. Indeed, the 56.1 ml/kg/min VO2peak of the Low group was equivalent to that some authors refer to as competitive [24].

Previous investigators have reported that fiber type may play a large role in determining cycling efficiency. Coyle et al. [1992] found a significant positive correlation between % type I fibers and both GE and DE (for subjects with similar VO2max at 80 rpm) [8]. Horowitz et al. linked performance, efficiency and fiber type, suggesting that for a similar oxygen uptake subjects with a higher % type I fibers produced more power in a 1 h performance test [13]. While fiber type was not measured in this study highly trained endurance athletes have been shown to have a higher % type I fibers [7,27] and might therefore be expected to exhibit greater efficiency; we however found no data to support this supposition.

Although our findings agree with those of several investigators, they contrast with those of Mallory et al. [20]. Those investigators used intermittent protocol and workloads corresponding to 30, 50, 70 and 90% of lactate threshold and reported a significant


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negat ve correlation between DE and VO_{2peak} and a significant positive correlation between their measure of economy (measured as the slope of the linear regression line that describes the relationship between VO_{2} and mechanical work done) and VO_{2} peak. We did not observe either of these relationships in our data. The reason for the discord between studies is not clear but may be related to differences in subjects' cycling experience between studies. All subjects participating in this study were experienced cyclists who regularly engaged in cycling. The low mean VO_{2peak} (43.9 [34.3–59.2] mL/kg/min; mean [range]) of the subjects in the study of Mallory et al. suggests that a lack of core cycling experience amongst some subjects may explain the differing conclusions.

We are unable to form any conclusions regarding the effect of training on efficiency based on the results of this study, because training was not an independent variable and differences between individuals in VO_{2peak} and W_{peak} will be partly due to genetic differences rather than training.

In summary, we examined several measures of cycling efficiency in cyclists who varied widely in their cycling ability; the subjects included recreational riders and world-class professionals. Our data indicated no differences between groups in GE (measured at an absolute mechanical power or at a relative intensity), DE or EC. In addition, while there was a small (R^2 = 0.06) but significant correlation between EC and peak aerobic power, there were no significant relationships between either GE or DE and measures of aerobic capacity. Thus, our data suggest that the cycling efficiency of elite cyclists is not different from that of trained or novice cyclists and therefore is not a predictor of success in elite level cycling.

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References
