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

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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 (VO_2) and carbon dioxide production (VCO_2) using stoichiometric equations. Subjects (age 26 ± 7 yr, body mass 74.0 ± 6.3 kg, Wpeak 359 ± 40 W and VO_2-peak 62.3 ± 7.0 mL/kg/min) were divided into 3 groups on the basis of their VO_2peak (< 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) at 165 W (GE_{165}), GE at the same relative intensity (GE_{final}), 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_{final}, DE or EC and VO_2peak. Based on these data, we conclude that there are no differences in efficiency and economy between elite cyclists and recreational level cyclists.

Key words
Gross efficiency · delta efficiency · economy · VO_2peak

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

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reduction in VO_2 for a given steady state work rate after a 21-day high altitude mountaineering expedition. Hochachka et al. also observed changes in efficiency with altitude; long-term high-altitude residents were found to exhibit higher mechanical efficiencies than trained low-altitude residents [12]. Passfield and Doust reported a reduction in GE following either a maximal 30 s sprint or 5 min performance test [26]. Recently McDaniel et al. isolated pedal speed (m/s) and pedalling rate (rpm) using different crank lengths and cadences and reported that delta efficiency (DE) increased with pedal speed (a marker for muscle shortening velocity) [22]. Coyle et al. found a positive correlation between GE, DE and % type I fibers [8]. Finally, Ferguson et al. reported a contraction speed dependant change in efficiency with passive elevation of muscle temperature [9].

Although the factors mentioned above are known to influence efficiency we find it fascinating that within the majority of the literature two markers for endurance cycling success, cycling experience and aerobic capacity, have NOT been reported to influence cycling efficiency [2,21,24,29]. While the greater part of the literature has found no relationship between these factors, there are some suggestions that differences in these variables may affect cycling efficiency. Lucia et al. compared professional and elite cyclists and observed a lower VO_2 (mL/kg/min) at one workload (300 W) during an incremental exercise test, although efficiency was not calculated [19]. In a later study an inverse relationship between VO_2max and cycling efficiency in "world-class" cyclists was reported [18]. However the data suggest exceptionally high values for efficiency and have recently been questioned [15]. The idea of a link between aerobic capacity and cycling efficiency is an appealing one as it is theoretically possible that training improves efficiency. It is certainly well known that training can modify the physiology and biochemistry of humans [27] and it seems possible that such plasticity may extend to metabolic 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. With this in 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 efficiency was different in cyclists of different abilities. To accomplish that purpose, we used a cross-sectional design and recruited a subject population that varied widely in aerobic capacity.

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 international governing body for cycling, the Union Cycliste Internationale (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 < 60 mL/kg/min (Low, N = 26), 60 – 70 mL/kg/min (Med, N = 27) and > 70 mL/kg/min (High, N = 16). Group characteristics are shown in Table **1**. Individual values of VO_2peak ranged from 3.41 to 6.20 L/min and the overall mean was 4.67 ± 0.69 L/min.

All subjects performed an identical graded exercise test to exhaustion on an electrically braked cycle ergometer (Lode Excalibur 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 stoichiometric 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 subjects' position on the ergometer was adjusted to match their accustomed 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. Exceptions to this were nine subjects for whom the test began at 165 W. Subjects were asked to maintain their cadence at between 80 – 90 rpm and were given visual feedback from the Lode control box in order to do this. Once the RER rose consistently above 1.00 for an entire workload, the measures of energy expenditure were no longer valid and maintenance of cadence was no longer necessary but exercise was continued to exhaustion in order to determine VO_2peak and Wpeak. VO_2peak was defined as the highest oxygen uptake value observed during the incremental 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 increment. 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

Group	*N*	*Age (years)*	*Body mass (kg)*	*Height (cm)*	*VO_2peak (mL/kg/min)*	*VO_2peak (L/min)*	*Wpeak (W)*
Low	26	27.3 ± 1.8	75.2 ± 1.2	180 ± 1	56.1 ± 0.8*	4.20 ± 0.05*	339 ± 6^{ab}
Med	27	24.0 ± 1.1	73.5 ± 1.4	181 ± 1	64.2 ± 0.5*	4.72 ± 0.08*	366 ± 7^{c}
High	16	25.5 ± 1.4	70.9 ± 1.6	182 ± 2	75.2 ± 1.0*	5.32 ± 0.12*	403 ± 8

All data are mean ± SE. * = significantly different from other 2 groups ($p < 0.0001$). ^{a} = significantly different from High ($p < 0.0001$). ^{b} = significantly different from Med ($p < 0.05$). ^{c} = significantly different from High ($p < 0.01$)

high in carbohydrate was consumed. Previously (unpublished data) we used a repeated measures design to compare gross efficiency between the fasted (min 10 h fast) and fed (10 h fast followed by 75 g of glucose 45 min prior to exercise) states on gross efficiency. There were no significant differences in GE between trials ($p = 0.836$).

Expired gas was sampled throughout the test using an online breath-by-breath gas analyzer (Oxycon Alpha, Mijnhardt, Bunnik, The Netherlands). Recordings were made as the mean of eight breaths and VO_2, VCO_2 and V_E were averaged every 30 s. The online system was calibrated prior to each test with both room air (20.93% O_2 and 0.03% CO_2) and a gas mixture (4.95% CO_2, 95.05% N) in line with the manufacturer's guidelines. The online gas analyzers were connected to a computer that calculated VO_2 and VCO_2 using conventional equations [17]. Rate of energy expenditure was calculated using the formula of Brouwer [3]:

Rate of Energy Expenditure
$(J/s) = [(3869 \cdot VO_2) + (1195 \cdot VCO_2)] \cdot (4186/60) \cdot 1000$

Gross efficiency GE, DE, EC and the cost of unloaded cycling (CUC) were subsequently calculated from measures of the rate of energy expenditure and mechanical power produced (work rate). GE was calculated as the ratio of work rate : rate of energy expenditure expressed as a percentage:

$GE (\%) = (\text{Work Rate [W]}/\text{Energy Expended [J/s]}) \cdot 100\%$

For clarity only the GE at 165 W (GE_{165}) and the GE at the last workload before the RER exceeded 1.00 (GE_{final}) is presented. Both DE and CUC were calculated from the linear regression for work rate vs. rate of energy expenditure in which CUC represents the intercept and DE represents the inverse of the slope of that relationship [8]. The cost of unloaded cycling (CUC) and DE were calculated from the pooled data of each group. EC was calculated from the mean of VO_2 data in the 50–70% VO_2peak range as the work done per liter of oxygen consumed expressed as kJ/L:

$EC (kJ/L) = (\text{Work Rate [W]}/\text{Oxygen Consumption [L/min]}) \cdot 0.06$

The ergometer was calibrated by measuring reactive torque at constant rotational velocity under varying loads prior to the start and at the end of the study. The error in the work rate displayed by the ergometer was found to be within 1% between 50 and 500 W.

The data from each individual were sorted into three groups according to VO_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.

All data are presented as mean ± SE except where described otherwise. A one-tailed Pearson product moment was used to calculate the correlation between GE, DE, EC and VO_2peak.

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_2peak (expressed as both mL/kg/min and L/min) and Wpeak.

The data representing the measures of efficiency and economy are presented in Table 2. There were no significant differences between groups for GE_{final}, GE_{165}, DE or EC. Data illustrating the relationship between GE_{165} (%) and VO_2peak (mL/kg/min) are shown in Fig. 1. There was no significant relationship between the two variables with the relationship described by the formula $y = -0.0348x + 20.752$ ($R^2 = 0.0372$). In a similar fashion there were no significant correlations between GE_{165}, GE_{final}, DE and VO_2peak (mL/kg/min or L/min). There was a weak significant correlation ($R^2 = 0.06$, $p < 0.05$) between Wpeak and EC, which is shown in Fig. 2, however EC was not significantly correlated with VO_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.

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

Group	*GE_{final} (%)*	*GE_{165} (%)*	*DE (%)*	*ED (kJ/L)*
Low	18.8 ± 0.6	18.6 ± 0.3	22.4 ± 0.4	4.3 ± 0.1
Med	18.6 ± 0.8	18.8 ± 0.4	21.6 ± 0.4	4.3 ± 0.1
High	18.9 ± 0.2	17.9 ± 0.3	21.2 ± 0.5	4.2 ± 0.1

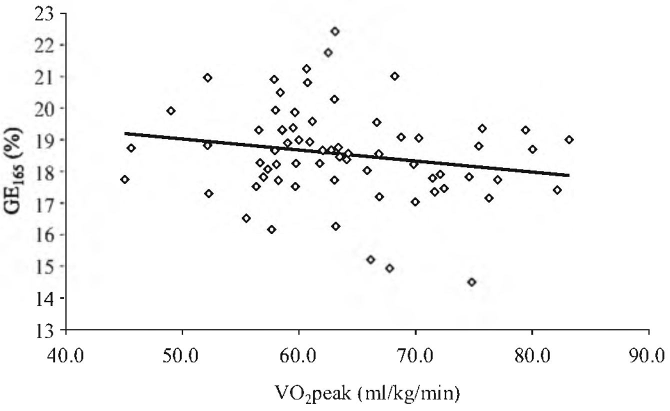

Fig. 1 Data illustrating the relationship between GE_{165} (%) and VO_2peak (mL/kg/min). The two variables are not significantly correlated, the formula describing the relationship is $y = 0.0348x + 20.752$; $R^2 = 0.0372$.

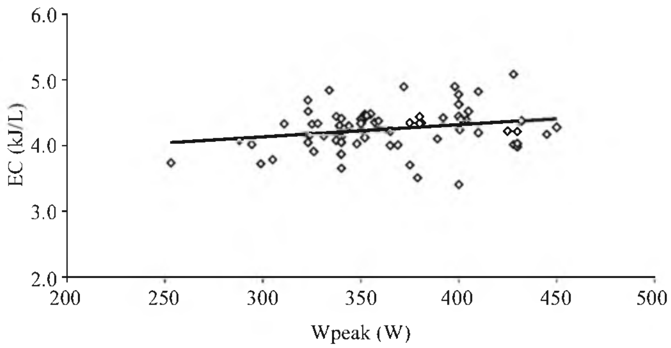

Fig. 2 Data illustrating the relationship between EC (kJ/L) and Wpeak (W). There is a weak significant correlation between the two variables ($r = 0.240$, $p < 0.05$), the formula describing the relationship is $y = 0.0019x + 3.5735$; $R^2 = 0.06$.

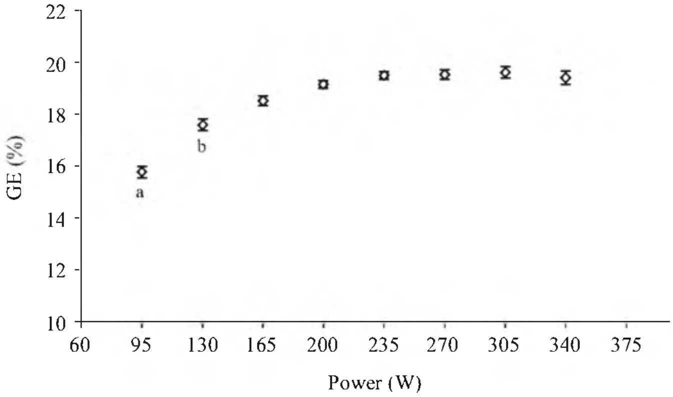

Fig. 3 Data illustrating the relationship between mechanical power output (W) and gross efficiency (%). a = significantly different from all other points ($p < 0.0001$). b = significantly different from all points 165 – 340 W ($p < 0.01$).

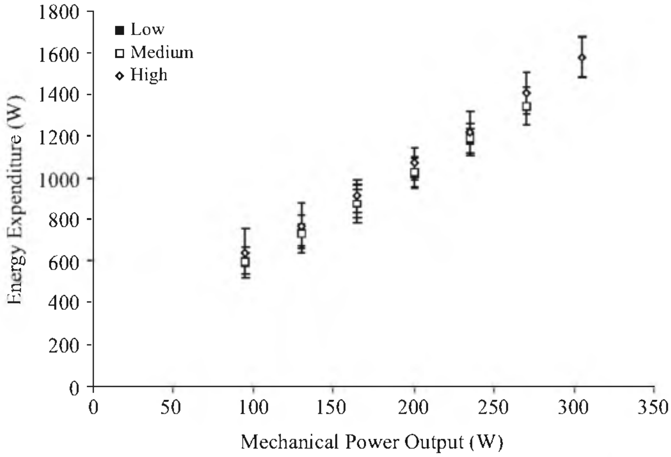

Fig. 4 The relationship between energy expenditure (W) and mechanical power output (W). Data is presented as group mean ± SD at each workload.

The metabolic cost of producing a given mechanical power output is shown in Fig. **4**. There were no significant differences between groups at any mechanical power. CUC was 141 ± 25 W (N = 26), 148 ± 17 W (N = 27) and 165 ± 22 W (N = 16) for the Low, Medium and High groups respectively. There were no significant differences between groups. The mean R^2 values for the regression lines used to calculate DE and the CUC were 0.992 ± 0.001, 0.990 ± 0.002 and 0.988 ± 0.003 for Low, Med and High respectively.

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 of 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 VO_2 to reach steady state. Data from our laboratory compared VO_2 and VCO_2 data collected in the last 2 minutes of each stage using this protocol with VO_2 and VCO_2 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 VO_2 and VCO_2 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 V_E could affect the accuracy of the measures of energy expenditure via the relationship between substrate oxidation and VCO_2. However, given the low relative intensity of the 165 Wstage (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 V_E on GE_{165}. In addition, while it is possible that hyperventilation could affect measures of energy expenditure at GE_{final}, where the relative workload was greater (76 ± 2, 76 ± 3, 80 ± 2% of Wmax for Low, Med and High respectively), the comparable relative intensity suggests that this would affect each group to a similar degree. Finally, if VCO_2 were to significantly lag behind VO_2 it could has 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/L).

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 VO_2max and distance runners with high VO_2max 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 VO_2max 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 VO_2peak 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 with a large range in their VO_2peak, are consistent with previous reports utilizing smaller ranges in VO_2peak. 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 VO_2 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 (GE_{final}, the GE at the last workload before the RER exceeded 1.00) and the same absolute exercise intensity (GE_{165}). 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 GE_{165} 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 VO_2 group would exhibit greater GE_{final} 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 VO_2peak of our groups. Specifically, the VO_2peak 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 VO_2peak. This difference was reduced at VO_{2final} (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 VO_2peak 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 VO_2max 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 negative 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 Wpeak 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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