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Improved Gross Efficiency during Long Duration Submaximal Cycling Following a Short-term High Carbohydrate Diet

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Key words
- cycling
- carbohydrate
- gross efficiency
- submaximal
- diet

Abstract

To assess the effect of dietary manipulation on gross efficiency (GE), 15 trained male cyclists completed 3×2 h tests at submaximal exercise intensity (60% Maximal Minute Power). Using a randomized, crossover design participants consumed an isoenergetic diet (~4000 kcal.day^{-1}) in the 3 days preceding each test, that was either high in carbohydrate (HighCHO, [70% of the total energy derived from carbohydrate, 20% fat, 10% protein]), low in carbohydrate (LowCHO, [70% fat, 20% carbohydrate, 10% protein]) or contained a moderate amount of carbohydrate (ModCHO, [45% carbohydrate, 45% fat, 10% protein]). GE along with blood lactate and glucose were assessed every 30 min, and heart rate was measured at 5 s intervals throughout. Mean GE was significantly greater following the HighCHO than the ModCHO diet (HighCHO = 20.4% ± 0.1%, ModCHO = 19.6 ± 0.2%; $P < 0.001$). Additionally, HighCHO GE was significantly greater after 25 min ($P = 0.015$) and 85 min ($P = 0.021$) than in the LowCHO condition. Heart rate responses in the HighCHO condition were significantly lower than during the LowCHO tests ($P = 0.005$). Diet had no effect on blood glucose or lactate ($P > 0.05$). This study suggests that before the measurement of gross efficiency, participants' diet should be controlled and monitored to ensure the validity of the results obtained.

Introduction

The laboratory assessment of gross efficiency during cycling is an area of growing interest, and has been reported as a key determinant of cycling performance [22]. A number of studies have investigated the laboratory practice of recording these measures [19,23,28,32], the impact of training status and interventions [1,7,15–17,26], gender [3,18] and adaptations that could result in improved efficiency [5,9,12,24,25,33]. Furthermore, it is suggested that there are potential performance benefits of improved efficiency as Jeukendrup and Martin [21] calculated that increasing gross efficiency by 1% for a 70 kg cyclist who can maintain a power output of 400 W for 1 h, would result in a 48 s improvement for a time trial over 40 km.

However, almost all of the literature cited has included little or no data on the nutritional status of participants prior to their laboratory assessment. This is somewhat problematic because early papers in this field have reported differences in cycling efficiency with altered carbohydrate intake during the period leading up to assessment [20,27]. Unfortunately, these early papers did not maintain the exercise intensity during their experimental protocols, and as time elapsed and fatigue ensued, the work rates were altered between trials. Altering work rates has been shown to influence the efficiency values obtained [6,11,30], therefore limiting the application of both Jansson and Neufer et al. [20,27]. Additionally, the later work of Dumke et al., [8] alluded to altered efficiency values with nutritional intervention but likewise did not maintain exercise intensity across different conditions. Therefore, it could be suggested that in altering the work rate, one would expect efficiency values to change regardless of nutritional intervention. Notwithstanding the limitations mentioned above, these studies suggest that nutritional interventions could produce alterations in efficiency that appear similar in magnitude to those reported through other interventions/scenarios such as training status and training interventions [1,16,17]. Despite numerous studies on dietary manipulation, there are a limited number of studies that present effi-

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ciency data, or the complete data set required to calculate efficiency from indirect calorimetry during steady state conditions (work rate, $\dot{V}O_2$, and respiratory exchange ratio). Therefore, the aim of this study was to investigate the effect of pre-exercise dietary manipulation on gross efficiency measures during steady state cycling at a fixed work rate.

Methods
▼
Participants
15 healthy trained male cyclists gave their written informed consent to participate in the investigation following approval from the Ethics Committee of Canterbury Christ Church University, UK. In addition, this research meets the ethical standards of the International Journal of Sports Medicine (IJSM) as outlined by Harriss & Atkinson [13]. All potential participants completed a general health questionnaire. The physical parameters of the participants are as follows: age 40 ± 9 years, weight 75.7 ± 8.8 kg, height 179 ± 8 cm and maximal oxygen uptake ($\dot{V}O_{2max}$) 56.3 ± 7.0 ml·kg^{-1}·min^{-1} (mean ± SD).

Experimental protocol
All exercise tests were undertaken on an electronically braked cycle ergometer (Schoberer Radmesstechnik, Julich, Germany). Each subject attended the laboratory on 4 separate occasions in an environment maintained at 20.4 ± 1.2 °C, 758 ± 6 mmHg and 48.6 ± 6.4 % humidity. Visit 1 comprised an incremental exercise test to exhaustion to determine maximal minute power (MMP) as the highest 60 s power during the test, with maximum oxygen uptake ($\dot{V}O_{2max}$) being defined as the maximum oxygen consumption over a 60 s period. Visit 1 also acted as a familiarization trial in which the participant was made aware of the testing procedure and also ensured that they could complete the desired level of exercise. Visits 2, 3 and 4 were exercise trials involving completion of a set duration of exercise (2-h) at constant exercise intensity (60 %MMP). Prior to visits 2, 3 and 4, participants consumed a diet for 3 days that was either high in carbohydrate (HighCHO), low in carbohydrate (LowCHO) or contained a moderate amount of carbohydrate (ModCHO). The study was a randomized, crossover design with each experimental trial separated by a minimum of 5 days.

Visit 1
Participants performed an incremental exercise test to volitional fatigue. This was comprised of an initial intensity of 100 W with a gradual increase in the exercise intensity (5 W every 15 s). The test was terminated when cadence dropped below 50 rpm despite standardized verbal encouragement. Ventilation, oxygen uptake ($\dot{V}O_2$), and carbon dioxide production ($\dot{V}CO_2$) were measured throughout the exercise test (Oxycon Pro, Jaeger, Germany). In addition, heart rate was monitored continuously via telemetry (Polar S725X, Polar Electro Oy, Finland). Following a period of rest, participants then completed a familiarisation of the protocol for Visits 2–4, wherein each cyclist's habitual cycling position was recorded and standardized for all subsequent trials in order to minimize the influence of different riding position efficiency as reported by Faria [10].

Visits 2–4
Participants arrived at the laboratory in a post-prandial state following ingestion of a meal ~4 h prior to the visit. The experimental trials were performed at the same time of day to avoid any circadian variance. On arrival at the laboratory participants were fitted with a heart transmitter and their weight was recorded. After a brief warm-up (2 min at each of the following intensities 20 %, 30 %, 40 %, 50 % & 60 % MMP), participants began the exercise test. The cycle ergometer was set to maintain a fly wheel resistance equivalent to 60 % of the participants MMP. Participants viewed pedal cadence throughout the trials and maintained a constant self-selected cadence throughout the tests (± 1 rpm). A fan was placed 1 m in front of the participant to provide some cooling and air flow during the exercise. Heart rate, speed and power output were recorded continuously throughout the entire protocol, while the participants were blinded to this information. At set intervals during the trial (every 30 min of the trial completed) participants' respiration was recorded for a period of 10 min via breath-by-breath analysis (Oxycon Pro, Jaeger, Germany). Regular blood samples were also collected to assess plasma glucose and lactate concentrations. During Visit 2, participants were instructed to drink ad libitum throughout the exercise test, and the volume of water ingested was then replicated for subsequent trials (Visits 3 & 4). At the end of the test, the participant's body weight was again measured to assess hydration status.

Determination of gross efficiency
The calculation of gross efficiency divides the work accomplished by the total energy cost required to do the work:

Gross Efficiency % = (Work Done/Energy Expenditure)*100

In order to establish the 'Work Done', the last 5 min of each 10-min respiratory collection was averaged to ascertain mean $\dot{V}O_2$ and Respiratory Exchange Ratio (RER). The calorific equivalent of O_2 was then determined from the corresponding RER according to the table of Zuntz [34].

Thus, 'Work Done' (kcal.min^{-1}) = $\dot{V}O_2$ (L.min^{-1}) × kcal.L^{-1} of O_2

In order to establish the 'Energy Expenditure', the mean power for the last 5 min of each 10-min respiratory collection was determined and converted into kcal.min^{-1} via the following equation:

'Energy Expenditure' (kcal.min^{-1}) = Power (W) × 0.01433

Dietary design
In order to establish habitual dietary intake, participants were asked to record their food intake for a 3-day period prior to Visit 1. Participants were provided with diet record sheets and written instructions to facilitate reliable and accurate dietary records. Additionally participants were encouraged to weigh all foods where possible or to otherwise estimate based on household portion sizes. This diet was then analysed by a trained researcher (CompEat Pro 5.8.0) to assess daily intakes of the total energy derived from carbohydrate (51.8 ± 5.7 %), fat (29.8 ± 6.1 %) and protein (15.6 ± 2.8 %) in addition to overall energy intake (2 817 ± 631 kcals · day^{-1}). Participants were then prescribed a diet (via the use of enforced dietary requirements) to follow in the 3 days prior to each exercise test. Actual food intake was closely monitored via the use of food diaries, and all participants gave verbal confirmation of adherence to each diet. There were 3 different diets to follow in the 3 days leading to Visits 2, 3, 4

respectively. Diets of similar design have previously been reported to alter pre-exercise muscle glycogen concentrations [2,4,31]. All diets were isoenergetic (~4000 kcal·day^{-1}). The 3 diets used in the current investigation were as follows:
HighCHO – 70% Carbohydrate, 20% Fat, 10% Protein.
LowCHO – 20% Carbohydrate, 70% Fat, 10% Protein.
ModCHO – 45% Carbohydrate, 45% Fat, 10% Protein.
In addition to following the diet, participants were asked to refrain from vigorous exercise and caffeine ingestion during the 3-days prior to each visit.

Statistical analysis

Statistical analysis was carried out using the SPSS computer software, version 14.0 (SPSS Inc., USA). For all physiological parameters, specific differences between the 3 trials were determined using a repeated measures ANOVA (3 measures of diet by 4 repeats of time) with specific differences determined using a Bonferroni correction post hoc. If normal distribution was not achieved, a non-parametric equivalent was used. The level of probability for rejecting the null hypothesis in all cases was set at $P \leq 0.05$. Data are reported as mean and standard deviation (mean ± SD), unless otherwise stated.

Results

GE decreased significantly with time across all trials ($P<0.001$, ▶ **Fig. 1**), however this decrease was significantly attenuated in the HighCHO condition (Mean HighCHO GE = 20.4% ±0.1%, Mean ModCHO GE = 19.6 ± 0.2%; $P<0.001$). More specifically, it appears that the majority of this difference occurred at the 25–30 min and 85–90 min time points as HighCHO GE measures were significantly higher in comparison to the other 2 trials (25–30 min: HighCHO = 21.2 ± 1.7%, LowCHO = 20.7 ± 2.0%, ModCHO = 20.3 ± 1.3%; P = 0.015, P = 0.032. 85–90 min: High CHO = 20.1 ± 1.9%, LowCHO = 19.6 ± 1.5%, ModCHO = 19.3 ± 1.8%; P = 0.021, P = 0.041). There were no significant differences in GE between the LowCHO and ModCHO trials at any time point ($P>0.05$).
Heart rate was significantly lower in the HighCHO trial than during the LowCHO trial (P = 0.005), this difference was apparent at all time points during the exercise test (▶ **Fig. 2**). There were no significant differences in blood lactate or blood glucose concentrations during the tests ($P>0.05$, ▶ **Fig. 3, 4**), or between the different dietary conditions ($P>0.05$).

Discussion

The aim of this investigation was to see if dietary manipulation could alter the laboratory assessment of gross efficiency during cycling. The results presented indicate that a high carbohydrate intake in the 3 days prior to an exercise assessment increased the efficiency values of trained cyclists by ~4% compared to moderate carbohydrate conditions.
These results support the data presented by Jansson [20], Neufer et al., [27] and Dumke et al., [8] who reported alterations in exercise efficiency scores with altered carbohydrate status. As these previous studies utilized time to exhaustion tests, their data is limited for the purposes of calculating GE due to fatigue related reductions in the exercise intensity as the trials progressed. This is particularly problematic in the assessment of efficiency due to the energy required for basal metabolism decreasing proportionally to the increase in exercise intensity. However, in the current study we utilized a fixed exercise intensity at 60% MMP,

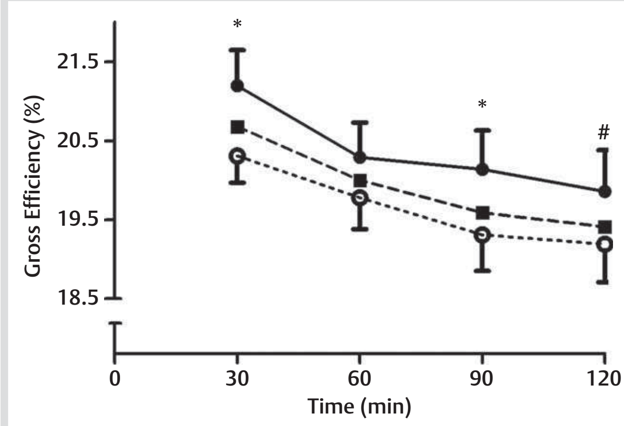

Fig. 1 Gross efficiency with time during the HighCHO [●], LowCHO [■] and ModCHO [○] conditions (mean ± SEM). *HighCHO significantly greater than either of other 2 conditions ($P<0.05$). # Significant decrease in gross efficiency with time across all conditions ($P<0.001$).

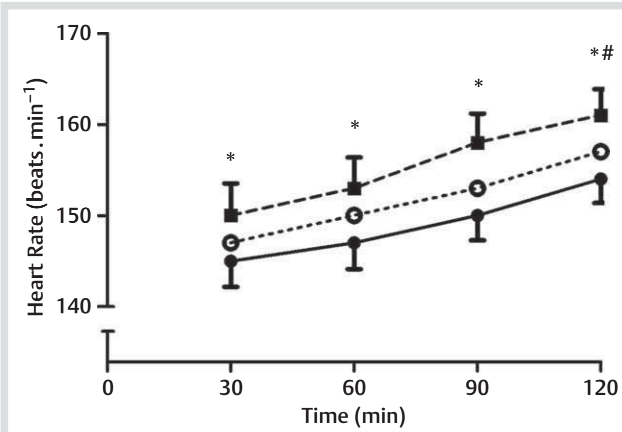

Fig. 2 Heart rate with time during the HighCHO [●], LowCHO [■] and ModCHO [○] conditions (mean ± SEM). *Significantly lower heart rate in HighCHO condition vs. LowCHO condition ($P<0.05$). # Significant increase in heart rate with time across all conditions ($P<0.001$).

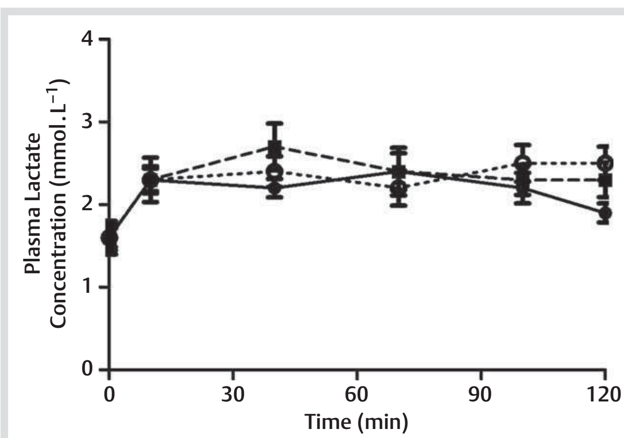

Fig. 3 Plasma lactate concentration with time during the HighCHO [●], LowCHO [■] and ModCHO [○] conditions (mean ± SEM).

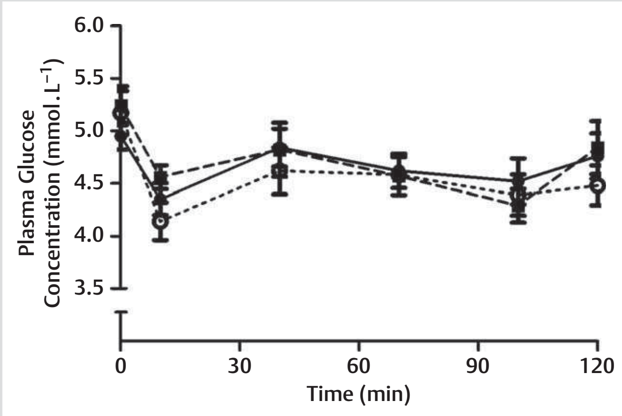

Fig. 4 Plasma glucose concentration with time during the HighCHO [●], LowCHO [■] and ModCHO [○] conditions (mean ± SEM).

Table 1 Differences in $\dot{V}O_2$, RER & Gross efficiency between different dietary conditions.

Dietary Condition	Time (min)	$\dot{V}O_2$ ($L.min^{-1}$)	RER	Gross efficiency (%)
High CHO	25–30	2.93 ± 0.39	0.91 ± 0.04	20.20 ± 1.72*
	55–60	3.04 ± 0.36	0.89 ± 0.04	20.35 ± 1.55
	85–90	3.06 ± 0.36	0.89 ± 0.03	20.13 ± 1.88*
	115–120	3.02 ± 0.52	0.86 ± 0.03	20.01 ± 2.14
Low CHO	25–30	3.02 ± 0.39	0.86 ± 0.06	20.72 ± 1.91
	55–60	3.09 ± 0.37	0.84 ± 0.04	20.28 ± 2.26
	85–90	3.18 ± 0.35	0.83 ± 0.03	19.64 ± 1.52
	115–120	3.26 ± 0.40	0.83 ± 0.03	18.99 ± 1.86
Mod CHO	25–30	3.02 ± 0.25	0.89 ± 0.03	20.34 ± 1.32
	55–60	3.09 ± 0.25	0.88 ± 0.04	20.00 ± 1.71
	85–90	3.18 ± 0.21	0.86 ± 0.03	19.33 ± 1.78
	115–120	3.19 ± 0.31	0.85 ± 0.03	19.01 ± 1.14

(All data mean ± SD, n = 15) *Significantly higher in High CHO condition vs. other conditions ($p \leq 0.05$)

thereby negating the problem of a higher workload while on a high carbohydrate diet as in Dumke et al. [8].

The findings from this current study highlight the requirement for any researcher in this field to consider strict control of pre-exercise nutrition. Indeed, where comparisons between participant groups have been made previously, the data reported here might account for a reasonable proportion of the differences found. When comparing different ability levels of cyclists, gross efficiency has been reported to be ~1 % better for the 'trained' participant groups [15]. However, it could also be assumed that this particular participant group may eat a higher carbohydrate diet compared to those individuals that do not engage in competition. If this were the case, then our data would suggest some of the difference in efficiency reported between ability levels could be attributed to nutritional influences. The findings from the current study might suggest that further study comparing training status should be revisited with a strict control of pre-exercise diet. Longitudinal studies may also have to follow a similar consideration. The efficiency data collected over one year [16], 5 years [29], or 7 years [7] may have been susceptible to alterations in habitual diet prior to assessments over this period, which in turn are considerations that should now be made when interpreting this data. Because it is unlikely that the trained participants in the studies cited above would follow a low carbohydrate diet prior to testing, the magnitude of the alterations in efficiency may not be as great as those observed in the current investigation. Nonetheless, this study suggests that dietary factors are clearly important and may have influenced results from previous investigations.

The implications of the findings in this current study may be wider than simply ensuring reproducible comparisons of laboratory efficiency measures. The data suggests that individual trained participants expend less energy for a fixed workload when they consume a high carbohydrate diet. The attenuated drop in exercise efficiency when consuming a high carbohydrate diet is similar to the findings of Dumke et al., [8], who concluded that part of the performance-improving capabilities of carbohydrate ingestion may be due to the better maintenance of metabolic efficiency. In other words, individuals who consume a high carbohydrate diet in the manner prescribed in this study reduce their energy expenditure and thus contribute to improved performance in other forms of laboratory assessment/protocols. In order to verify this, future research should involve some form of 'performance assessment' e.g. time trial, to ascertain whether the improvements in efficiency are linked to an improvement in performance.

The physiological data recorded during the exercise trials may provide some answers to the origins of the differences in efficiency recorded. The changes in efficiency were primarily due to changes in $\dot{V}O_2$, with RER differing by only 0.03 units between trials (▶ **Table 1**). While the reduced heart rate in the HighCHO trial may be linked to the reduction in oxygen cost, the magnitude of the lower heart rate (~6 $beats.min^{-1}$) does appear to be a rather large change. One consideration could be an elevation in water storage with the HighCHO diet, with this liberated water contributing to a reduction in heat stress [14] and cardiovascular demand during the HighCHO exercise test. However, this requires further investigation as no measures of core temperature were collected during the current study. Furthermore, this study did not find any significant differences in blood glucose or lactate concentrations between dietary conditions, thereby suggesting that the observed differences in gross efficiency were not due to improved maintenance of blood glucose levels or lower lactate production. Moreover, the major differences in this study were observed between the HighCHO and ModCHO conditions, suggesting that differences in gross efficiency are not simply as a result of absolute carbohydrate intake. It is also important to note that adherence to the prescribed diets was provided via verbal confirmation from participants and, as is the case with the majority of prescribed diet studies, one cannot be assured of total compliance. Additionally, while the prescribed energy intake of ~4000 $kcal \cdot day^{-1}$ was designed to elicit significant alterations in pre-exercise muscle glycogen levels, in terms of energy balance this may have been excessive for some participants and insufficient for others. So while the present investigation raises some interesting observations, this area requires further research before recommendations for the optimal diet for maximum gross efficiency can be provided.

In conclusion, significant differences in gross efficiency were obtained following alteration of participants' diet in the 3 days preceding assessment. This suggests that before the measurement of gross efficiency takes place, participants' diet should be carefully controlled and monitored to ensure the validity of the results obtained. From a performance perspective this research also suggests that at fixed work rates, overall energy expenditure is reduced following consumption of a short-term high carbohydrate diet.

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