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The effects of acute carbohydrate and caffeine feeding strategies on cycling efficiency.

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Abstract

Many research studies report and monitor cycling efficiency yet few report that nutritional intake was controlled across the period of assessment. To assess the effect of carbohydrate and caffeine on gross efficiency (GE), 14 cyclists ($\dot{V}O_{2max}$ 57.6 ± 6.3ml·kg^{-1}·min^{-1}) completed 4 x 2-hour tests at a submaximal exercise intensity (60% Maximal Minute Power). Using a randomized, counter-balanced crossover design, participants consumed a standardised diet in the 3-days preceding each test and subsequently ingested either caffeine (CAF), carbohydrate (CHO), caffeine+carbohydrate (CAF+CHO) or water (W) during exercise whilst GE and plasma glucose were assessed at regular intervals (~30mins). GE progressively decreased in the W condition but, whilst caffeine had no effect, this was significantly attenuated in both trials that involved carbohydrate feedings (W = -1.78±0.31%; CHO = -0.70±0.25%, p=0.008; CAF+CHO = -0.63±0.27%, p=0.023; CAF = -1.12±0.24%, p=0.077). Mean blood glucose levels were significantly higher in both carbohydrate ingestion conditions (CHO = 4.79±0.67 mmol·L^{-1}, p<0.001; CAF+CHO = 5.05±0.81 mmol·L^{-1}, p<0.001; CAF = 4.46±0.75 mmol·L^{-1}; W = 4.20±0.53 mmol·L^{-1}). In conclusion, carbohydrate ingestion has a small but significant effect on exercise-induced reductions in gross efficiency, indicating that cyclists' feeding strategy should be carefully monitored prior to and during assessment.

Introduction

Carbohydrate ingestion during exercise has frequently been found to have a positive effect on endurance performance (Below, Mora-Rodriguez, Gonzalez-Alonso & Coyle, 1995; El-Sayed, Balmer & Rattu, 1997; Jeukendrup, Brouns, Wagenmakers & Saris, 1997). During prolonged (>90-min) moderate intensity (~65%VO_{2max}) exercise there is evidence to suggest that the improvement in performance may be due to the preservation of high carbohydrate oxidation rates, thus delaying the onset of fatigue (Coyle, Coggan, Hemmert & Ivy, 1986). However it is currently unknown whether carbohydrate intake during exercise influences gross efficiency and subsequent performance during prolonged cycling. Indeed, it has been calculated that a 1% improvement in gross efficiency could lead to significant enhancements in performance (Jeukendrup & Martin, 2001).

Previously we have demonstrated that consumption of a short-term high carbohydrate diet prior to exercise can lead to improvements in gross efficiency under steady-state laboratory conditions (Cole, Coleman, Hopker & Wiles, 2014). Whilst these results demonstrate the influence of pre-exercise dietary interventions, many cyclists also utilise feeding strategies during competition and so the current study will aim to understand if these also have an influence on gross efficiency. Additionally, many studies have reported improvements in endurance performance following caffeine ingestion (Bell & McLellan, 2002; Ivy et al., 2009; Pasman, Van Baak, Jeukendrup & De Haan, 1995). The use of caffeine as an ergogenic aid is increasingly popular among athletes, particularly since its removal from the World Anti-Doping Agency's list of prohibited substances in 2004 (Lawrence, Wallman & Guelfi, 2012). Whilst several mechanisms, principally focussing on influences in the central nervous system (Tarnopolsky, 2008), have been purported towards this enhancement, little is known regarding the influence of caffeine ingestion on gross efficiency. If, as suggested, caffeine increases neuromuscular function during exercise then one might also expect a resultant increase in gross efficiency. . It would be of interest to understand whether this is in fact the case.

Furthermore, some studies have also reported greater performance improvements when both carbohydrate and caffeine are co-ingested than either independently (Cureton et al., 2007), possibly due to caffeine increasing the rate at which carbohydrate can be absorbed (Yeo, Jentjens, Wallis & Jeukendrup, 2005).

Despite widespread literature assessing carbohydrate and caffeine feedings during exercise, there are a limited number of studies that present efficiency 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). Of those from which we have been able to calculate gross efficiency, or in the very least been able to determine energy expenditure, it appears that consumption of either carbohydrate or caffeine, immediately prior to or during exercise, reduces gross efficiency or increases energy expenditure in comparison to that of a placebo (Coggan & Coyle, 1989; Dumke et al., 2007; Febbraio et al., 1996; Fletcher & Bishop, 2011; Ivy et al., 1983; Jenkins et al., 2008; McConnell, Kloot & Hargreaves, 1996; Neufer et al., 1987; Nikolopoulos, Arkinstall & Hawley, 2004; Schubert et al., 2014). However, it is difficult to quantify the practical value of the above findings as many of the studies mentioned did not involve fixed work intensity and so this complicates the interpretation of gross efficiency which is highly susceptible to alterations in work rate (Gaesser & Brooks, 1975). Therefore, this investigation will aim to clarify these results by specifically assessing the influence of acute carbohydrate and caffeine feeding strategies on gross efficiency during 2 hour steady-state submaximal cycling.

Methods

Participants: Fourteen healthy trained male cyclists gave their written informed consent to participate in the investigation. All potential participants completed a general health questionnaire. The participants had an age of 42.6 ± 8.4 years, mass of 76.7 ± 6.7 kg, height of 180 ± 5.9 cm and maximal oxygen uptake ($\dot{V}O_{2max}$) of 57.6 ± 6.3 ml·kg^{-1}·min^{-1} (mean ± SD). The study was approved by the Canterbury Christ Church University Ethics Committee prior to commencement.

Study Design: In a randomised, counter-balanced, cross-over design, each participant attended the laboratory on five separate occasions in an environment maintained at 19.6 ± 3.4 °C, 754 ± 8 mmHg and 54.1 ± 5.2 % humidity throughout. Visit 1 comprised of an incremental exercise test to exhaustion to determine maximal minute power (MMP), defined as the highest 60 second power output during the test, and maximum oxygen uptake ($\dot{V}O_{2max}$). Visit 1 also acted as a familiarisation trial in which the participants were made fully aware of the testing procedure and also ensured that they could complete the desired level of exercise. Visits 2-5 were experimental trials involving completion of a set duration of exercise (2 hours) at constant exercise intensity (60% MMP) following a single-blind supplementation protocol. Exactly 1 h prior to each experimental trial, participants were required to consume 250ml water and on two of those occasions, were also given 5mg·kg^{-1} body mass of caffeine (Blackburn Distributions, Blackburn, UK) to consume. This timing and dosage has been shown to enhance endurance performance (Bell & McLellan, 2002; Pasman et al., 1995). During all four 2 hour exercise tests, participants were provided with an equal volume (300 ml) of water every 30 min (total of 1.2 L over 2 hours) to ensure that they did not become >2 % body mass dehydrated. During two of the four experimental trials, 18 g of maltodextrin (Blackburn Distributions, Blackburn, UK) was added to each 300 ml of water to make 6 % carbohydrate solution. On one of the visits, to act as a 'control' neither caffeine nor carbohydrate was consumed. Thus, the design of the 4 experimental trials is outlined in **Table 1**:

******INSERT TABLE 1 NEAR HERE******

Prior to visit 2 participants consumed and recorded a diet for 3 days and this diet was then replicated for the 3 days preceding subsequent experimental trials. In addition to following their individual standardised diet (which was verbally confirmed by participants on arrival at the laboratory for each visit), participants were asked to refrain from vigorous exercise and caffeine and tobacco ingestion during the 3 days prior to each visit.

$\dot{V}O_{2max}$ determination and familiarisation: All exercise tests were undertaken on an electronically braked cycle ergometer (Schoberer Radmesstechnik, Julich, Germany). Participants performed an incremental exercise test to volitional fatigue. This comprised of an initial intensity of 100 W with a gradual increase in the exercise intensity (5 W every 15 sec). The test was terminated when cadence dropped below 50 rpm despite standardised 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). In order to establish if the participant had reached $\dot{V}O_{2max}$, two of the following three criteria had to be satisfied. 1) The cyclist's heart rate had to be within ±2 beats·min^{-1} of the age-calculated theoretical maximal heart rate, determined as 220 minus age. 2) The participants RER had to be greater than 1.1. 3) A plateau in the cyclist's $\dot{V}O_2$ (increase in $\dot{V}O_2$ <0.05 L·min^{-1}) in the last 30 seconds of the test. Following a period of rest, participants then completed a familiarisation of the protocol for Visits 2-5, during which each cyclist's habitual cycling position was recorded and standardised for all subsequent trials in order to minimise the influence of different riding position efficiency as reported by Faria (1992).

Experimental trials: Participants arrived at the laboratory post-prandial 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 the participants were fitted with a heart transmitter and their body mass 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 the resistance of the fly wheel to elicit 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 although this information was blinded to the participants. At set intervals during the trial (every 30 min of the trial completed) participants' respiration was recorded for a period of 10 minutes via breath-by-breath analysis (Oxycon Pro, Jaeger, Germany). 20 µl finger-prick blood samples were also collected (~30 min intervals) to assess plasma glucose and lactate concentrations (Biosen X030, EKF Industrie, Electronik GmbH, Barleben, Germany). Participants received no performance-related feedback (distance covered, average speed, $\dot{V}O_2$ or heart rate) during the trials and no results were given until completion of the entire study.

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 (Gaesser & Brooks, 1975)

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 (1901).

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

In order to establish the 'Energy Expenditure', the mean power for the last 5-mins 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) x 0.01433 (Astrand & Rodahl, 1988)

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 four trials were determined using a repeated measures

ANOVA (four measures of supplement by four repeats of time) with specific differences determined using a Bonferroni correction *post hoc*. The level of probability for rejecting the null hypothesis in all cases was set at $p<0.05$. Where significant differences were obtained, effect sizes were subsequently determined via the method of Cohen (1992). Data are reported as mean and standard error (mean ± SEM), unless otherwise stated.

Results

Gross Efficiency: Mean GE data are reported in **Table 2**. During the W+W trial, mean GE was significantly greater than in both W+CHO ($p=0.010$) & CAF+W ($p=0.030$) conditions.

******INSERT TABLE 2 NEAR HERE******

Additionally, **Figure 1.** demonstrates a significant decrease inmean GE with time in all conditions ($p<0.001$). Significant differences between trials can be observed at the 20-30 minute time point only, with W+W having higher GE measures than both W+CHO ($p=0.002$) & CAF+W ($p=0.038$) conditions .

******INSERT FIGURE 1 NEAR HERE******

When analysing the percentage decrease in efficiency from the 20-30 min measurement to that at the end of the test, it was determined that the decrease was significantly attenuated in both trials involving carbohydrate feedings when compared with the water-only condition (W = -1.78 ± 0.31 %; CHO = -0.70 ± 0.25 %, p=0.008, Cohen's *d* = 1.15; CAF+CHO = -0.63 ± 0.27 %, p=0.023, Cohen's *d* = 1.14; CAF+W = -1.12 ± 0.24 %, p=0.077, Cohen's *d* = 0.64, **Figure 2**).

******INSERT FIGURE 2 NEAR HERE******

Heart Rate: Mean heart rate increased with time in all conditions (p<0.001) but this was not influenced by supplementation (W+W = 144 ± 3 bpm; W+CHO = 145 ± 3 bpm, p=0.079; CAF+W = 144 ± 3 bpm, p=0.938; CAF+CHO = 143 ± 3 bpm, p=0.281).

Plasma Glucose & Lactate: Mean blood glucose levels were significantly higher in both carbohydrate feeding conditions vs. the water-only trial (W+W = 4.20 ± 0.53 mmol·L^{-1}; W+CHO = 4.79 ± 0.67 mmol·L^{-1}, (p<0.001, Cohen's *d* = 0.365); CAF+CHO = 5.05 ± 0.81 mmol·L^{-1} (p<0.001, Cohen's *d* =0.469); CAF+W = 4.46 ± 0.75 mmol·L^{-1}) and this increase appeared to be primarily as a result of significant decreases in plasma glucose concentration beyond the 40 min time point in both the W+W & CAF+W trials (**Figure 3**). There was no main effect of condition (p=0.412) or time (p=0.065) on blood lactate levels.

******INSERT FIGURE 3 NEAR HERE******

Respiratory Exchange Ratio (RER): There were no significant differences in the RER between any conditions (W+W = 0.87 ± 0.01; W+CHO = 0.87 ± 0.01, p=0.408; CAF+W = 0.87 ± 0.01, p=0.352; CAF+CHO = 0.87 ± 0.01, p=0.914).

Discussion

The aim of this investigation was to assess whether carbohydrate and caffeine feedings either independently, or together, could influence the laboratory assessment of gross efficiency during a 2 hour steady-state cycling trial. In the current study, it was observed that gross efficiency was significantly lower at the 20-30 minute time point for the two conditions involving carbohydrate or caffeine intake in comparison to that of when only water was consumed. Interestingly when carbohydrate and caffeine were consumed in-combination, there was no significant impact on gross efficiency.

One explanation for the lower gross efficiency under caffeine conditions might be to suggest increased lipolytic activity as proposed by Ivy and colleagues (1978). If this was the case, one would anticipate a lower RER as evidence of the higher oxygen cost of fat metabolism. However the data from the current investigation do not support this theory as there was no difference in the RER between the caffeine condition vs. the water-only condition.

The findings of this study are in agreement with several others which, although they did not report efficiency directly, permit efficiency determination from the data presented (Coggan & Coyle, 1989; Dumke et al., 2007; Febbraio et al., 1996; Fletcher & Bishop, 2011; Ivy et al., 1983; Jenkins et al., 2008; McConnell, Kloot & Hargreaves, 1996; Neufer et al., 1987; Nikolopoulos, Arkinstall & Hawley, 2004; Schubert et al., 2014). All of the reported studies demonstrate a trend for either a decrease in efficiency or increase in energy expenditure following ingestion of carbohydrate and/or caffeine. These observations may be attributed to increased energy expenditure as a result of digestion, absorption and the associated thermal losses (Jequier, 1986). The accumulated energy expenditure of these processes has been defined as specific dynamic action (SDA) (Secor, 2009). Interestingly, mean GE in the CAF+CHO was not significantly lower than the water-only condition, either across the whole exercise duration or at any given time point. This might suggest that when ingested in combination, caffeine may augment the carbohydrate uptake (Yeo et al., 2005) and thus the energy losses of digestion and absorption were not as great relative to the other conditions.

Nonetheless a difference of >1% in the mean GE measures of different conditions has important implications for the existing literature. A difference in GE of similar magnitude has previously been reported across different participant groups (Hopker, Coleman & Wiles, 2007) or following longitudinal data collection over different time periods (Coyle, 2005; Hopker, Coleman & Passfield, 2009; Santalla, Naranjo & Terrados, 2009). This data would suggest that some of the reported difference could be due to alterations in nutrient intake immediately prior to or during assessment. Whilst it would be expected that these studies undertook rigorous controls, the results of this investigation reinforce the need for investigators to ensure that participant's nutritional intake is monitored carefully for the period immediately prior to and during assessment. This should be in addition to standardisation of 3-day dietary intake prior to measurement which, as previously demonstrated, also influences gross efficiency (Cole et al., 2014).

The implications of the outcomes from the current study may be wider than simply providing recommendations for the laboratory assessment of gross efficiency. These data might suggest that for prolonged duration cycling events (≥2 hr), some of the observed benefits of carbohydrate feedings on performance (Currell & Jeukendrup, 2008; Davis et al., 1988; Wright, Sherman & Dernback, 1991) may be as a result of improvements in gross efficiency. This study demonstrated that whilst mean efficiency over the whole trial not higher overall, at the 2 hour time point the decrease in gross efficiency was significantly attenuated in the two conditions involving carbohydrate feedings. If the exercise was to continue beyond this time, as many tour stages and 1 day races often do, it is reasonable to suggest that if this trend were to continue, these conditions would actually sustain greater gross efficiency for longer.

An interesting paradox is presented when considering the outcomes of this investigation versus our previous work. When exercise is undertaken following ingestion of a high carbohydrate diet and ~ 4 h post-prandial, gross efficiency measures appear to be higher (Cole et al., 2014). Whereas when carbohydrate is fed during exercise as in the current study, this appears to have a detrimental effect on gross efficiency measures – at least in the early stages of exercise. This would support the notion that up until ~1 hour, the exercise demands are adequately met by the endogenous carbohydrate stores and rather than providing any additional benefit, carbohydrate intake may actually be detrimental to performance. An explanation for this different outcome is likely because the muscle glycogen stores are not depleted within 1 hour, even if undertaking maximal intensity exercise (Hawley, Schabort, Noakes & Dennis, 1997). Therefore, only once these stores start to become depleted can the ergogenic effect of exogenous carbohydrate metabolism have an influence, as observed in this study towards the 90-120 minute time points.

Whilst the current study limited its focus to the laboratory assessment of gross efficiency, it would be useful to measure the direct performance implications given that Jeukendrup & Martin (2001) suggest that a 1% difference in GE could elicit a 48 second improvement in performance over a 40 km time trial. Furthermore whilst undertaking all measures in a controlled laboratory setting allowed careful control of external variables in this study, it would be of value to establish whether the outcomes are replicated outdoors where the pacing strategies and power profiles vary considerably in comparison to the constant steady-state loads set on the SRM ergometer in the laboratory. More research is also needed to clarify the energetic cost of nutrient feedings during exercise and the potential impact of this on gross efficiency. Additionally future work may wish to consider the impact of different doses of carbohydrate and/or caffeine to examine whether increasing or lowering the intake might lead to more optimal gross efficiency measures.

Conclusions

Reductions in gross efficiency during a 2 hour submaximal cycling test are attenuated by carbohydrate ingestion whilst the consumption of caffeine has no benefit. As discussed above, this has implications for the laboratory assessment of gross efficiency and may have relevance to performance during cycling events of >2 hour duration.

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