Pre-exercise carbohydrate feeding and high-intensity exercise capacity: effects of timing of intake and carbohydrate concentration.

Stuart DR Galloway, Matthew JE Lott and Lindsay C Toulouse

Health and Exercise Sciences Research Group
School of Sport
University of Stirling
Stirling
SCOTLAND.
U.K.

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Correspondence to:
Dr Stuart Galloway
Health and Exercise Sciences Research Group
School of Sport
University of Stirling
Stirling
SCOTLAND.
U.K.
s.d.r.galloway@stir.ac.uk
Tel: +44 (0)1786 466494
Fax: +44 (0)1786 466477

ABSTRACT

The present study aimed to investigate the influence of timing of pre-exercise carbohydrate feeding (Part A), and carbohydrate concentration (Part B), on short-duration high-intensity exercise capacity. In Part A, seventeen males, and in Part B ten males, performed a peak power output (PPO) test, two familiarisation trials at 90% of PPO, and 4 (for Part A) or 3 (for Part B) experimental trials involving exercise capacity tests at 90% PPO. In Part A, the 4 trials were conducted following ingestion of a 6.4% carbohydrate/electrolyte sports drink ingested 30 (C30) or 120 (C120) minutes before exercise, or a flavour-matched placebo administered either 30 (P30) or 120 (P120) minutes before exercise. In Part B, the 3 trials were performed 30 minutes after ingestion of 0%, 2% or 12% carbohydrate solutions. All trials were performed in a double blind cross-over design following and overnight fast. Dietary intake and activity in the two days before trials was recorded and replicated on each visit. Glucose, lactate, heart rate and mood/arousal were recorded at intervals during the trials. In Part A, C30 produced the greatest exercise capacity (mean±SD; 9.0±1.9 min, $P<0.01$) compared with all other trials (7.7±1.5 min P30, 8.0±1.7 min P120, 7.9±1.9 min C120). In Part B, exercise capacity (min) following ingestion of the 2% solution (9.2±2.1) compared with 0% (8.2±0.7) and 12% (8.0±1.3) solutions approached significance ($p=0.09$). This study provides new evidence to suggest that timing of carbohydrate intake is important in short duration high-intensity exercise tasks, but a concentration effect requires further exploration.

INTRODUCTION

The majority of studies examining the effects of carbohydrate feeding on exercise performance and exercise capacity have focused on carbohydrate ingestion during prolonged exercise, or on pre-exercise carbohydrate feeding in the few hours or minutes before prolonged endurance activities (for reviews see Cermak & Van Loon, 2013; Temesi et al., 2011; Karelis et al., 2010; Jeukendrup & Killer, 2010). There has been limited focus on carbohydrate feeding prior to short duration (<10 min), high-intensity (>85% max), exercise tasks, presumably because it is acknowledged that muscle glycogen depletion will not be limiting during exercise of this nature. As a result, guidelines for pre-event fuelling focus on providing information about carbohydrate intake before endurance exercise tasks lasting longer than 60 minutes (Burke et al., 2011). Current guidelines specify that there is no requirement for ingestion of carbohydrate before events lasting less than 45 minutes. Furthermore, it is recognized that ingestion of carbohydrate in the immediate pre-exercise period (30-60 minutes before exercise) can reduce liver glucose output, stimulate glucose uptake and oxidation and induce a rebound hypoglycaemia in susceptible individuals (Williams and Lamb, 2008; Jeukendrup & Killer, 2010). Interestingly, these known metabolic effects of pre-exercise feeding have not been considered for their potentially beneficial impact on high-intensity short-duration exercise.

Pre-exercise elevation of blood glucose and insulin increases glucose uptake and oxidation in contracting skeletal muscle (Febbraio et al., 2000a,b; Tsintzas et al., 2000) through activation of the pyruvate dehydrogenase enzyme complex (PDC). It has also been shown that pharmacological activation of PDC reduces phosphocreatine degradation and muscle lactate accumulation during short intense muscle contraction protocols (Timmons et al., 1998). It could therefore be hypothesized that the correct timing and concentration of pre-exercise carbohydrate feeding, to maximize glucose uptake and oxidation, could aid in matching supply and demand for ATP by contracting skeletal muscle during short duration high-intensity exercise

tasks. A novel interpretation of this metabolic impact of pre-exercise carbohydrate feeding would be to suggest that an increased glucose uptake and oxidation early in exercise could help to delay the development of fatigue in high-intensity short-duration tasks. This would be particularly true for tasks lasting less than 10 minutes during which time the stimulus to carbohydrate oxidation would be at its greatest. To date, no studies have investigated this possible action of carbohydrate feeding prior to high-intensity exercise. Therefore, more research is needed to define the effects of carbohydrate feeding prior to short-duration high-intensity exercise before we fully dismiss any need for carbohydrate intake prior to high-intensity exercise tasks.

We therefore hypothesized that feeding carbohydrate 30 minutes before exercise would result in improved high-intensity exercise capacity compared with feeding 120 min before exercise, and we hypothesized that the size of this effect may reflect the pre-exercise elevation in plasma glucose concentration in a dose-response manner.

METHODOLOGY

The study was performed as two separate parts. Part A addressing the primary aim of examining timing of carbohydrate intake on high-intensity exercise capacity, and Part B addressing the secondary aim of the impact of carbohydrate concentration on high-intensity exercise capacity.

Participants

Participants in Part A were 17 male volunteers and in Part B were 10 male volunteers. All volunteers were recreationally active team sport players (Table 1). Prior to taking part in the study participants were fully informed, both through written and verbal information, as to the purposes of the study and of the risks involved. Pre-participation screening in the form of

general health questionnaires and physical activity questionnaires were administered prior to participation. Each participant then gave their written informed consent. The experimental protocols for Part A and Part B were both approved by the University of Stirling Ethics Committee. All volunteers involved in Part A and Part B of the study completed 3 preliminary visits prior to the main experimental trials. All sessions were conducted one week apart and at the same time of day, in the morning after an overnight fast (10-12 hours).

The preliminary visits required the participants to report to the laboratory for pre-screening followed by a maximal incremental exercise test, and for two high-intensity exercise capacity habituation trials. The maximal exercise test was conducted on an electrically braked cycle ergometer (Sensormedics Ergoline 900) to determine peak power output (PPO) using a modified method of Hawley and Noakes (1992). Briefly, the starting work load was calculated in respect to each subject's body mass (2.5W/kg) and increased by 50W after 150 seconds and thereafter increased by 25W every 150 seconds until volitional exhaustion (failure to sustain a cadence above 60 rpm). PPO was then calculated according to the formula: PPO = W_{final} + ([t/150] * *25*) where W_{final} is the final workload attained and t is the elapsed time achieved during the stage. 25 is a constant reflecting the load increase per stage. During the initial PPO assessment verbal encouragement was provided by the researchers.

Having calculated each participant's PPO, two practice trials were then undertaken on the cycle ergometer at 90% of their PPO and work was sustained until volitional exhaustion (cadence could not be sustained above 60 rpm). During these high-intensity exercise capacity tests encouragement was withheld and no music provided to ensure that participants were not influenced by the researchers/environment. Participants also completed a mood/arousal questionnaire (Brunel Mood Scale (BRUMS); Terry et al., 1999) and blood sampling procedures were performed. On completion of these preliminary visits the participants entered into the

experimental phase of the studies and either undertook four experimental trials for Part A or three experimental trials for Part B administered using a Latin square randomization procedure. Since Part A of the study was completed first we conducted an *a priori* sample size estimate based upon the Part A data but also based upon recruitment of a more homogenous group (of similar age, training status and peak power output) competing in University team sports. Our sample size estimate was based on 95% confidence limits, 80% power, pooled SD of 1 min and a mean difference detectable between trials of 1 min. This provided an estimate of n=8 for Part B and hence n=10 were recruited.

Experimental Procedures - Part A.

In Part A of the study, four experimental trials were undertaken in a double blind cross-over randomization design with 7 days between trials. Participants were asked to keep a food and activity diary for 48 hours prior to the first experimental trial and to not undertake any moderate or intense activity during the 24 hours before the trial. Participants then replicated their dietary intake and activity in the 48 hours prior to each of the subsequent experimental trials which was confirmed verbally on the morning of each trial using a checklist. All trials were carried out in the morning after an overnight fast (>10 hours). Each participant reported to the laboratory in the morning (between 8-10 a.m.) and body mass was recorded prior to completing an initial evaluation of mood/arousal using the BRUMS questionnaire. BRUMS has been used to successfully assess mood/arousal changes from pre- to post- exercise in previous studies (Milton et al., 2005; Terry et al., 2012). Following completion of the BRUMS a capillary blood sample was obtained for determination of baseline plasma glucose and plasma lactate concentration. Participants then ingested a single 500ml bolus of either a commercially available carbohydrate-electrolyte beverage (6.4% carbohydrate, 32g, C) or a flavour and colour matched placebo (0.1% carbohydrate, P). The composition of the drinks is shown in Table 2. On two of the trials there was a 30 minute seated rest period (C30 and P30) and on the other two a 2 hour

seated rest period (C120 and P120) between ingestion of the drink bolus and the start of the high-intensity exercise capacity test. Following the rest period (immediately before exercise) a further BRUMS questionnaire was completed and another capillary blood sample was obtained. A heart rate monitor was fitted and subjects were given a 5 minute warm up at half of their 90% PPO workload. After completion of the warm up participants cycled at 90% of PPO until volitional exhaustion. Heart rate was recorded throughout exercise and no verbal encouragement or music was provided on any of the trials. A final BRUMS questionnaire was completed immediately after the end of exercise and a final capillary blood sample was obtained 3 minutes following completion of exercise. A schematic of the protocol is shown in Figure 1.

Experimental Procedures - Part B.

In Part B of the study, three experimental trials were carried out in a single blind cross-over design with trials conducted one week apart. Participants also completed both a food and exercise diary to enable standardisation to occur within each participant as described for Part A. All trials were carried out in the morning after an overnight fast (>10 hrs). On arrival at the laboratory body mass was recorded prior to completing an initial evaluation of mood/arousal using the BRUMS questionnaire.

Following these initial measurements a small capillary blood sample was obtained for determination of baseline plasma glucose and lactate concentration. Participants then ingested either a flavour and colour matched placebo (0%), a dilute carbohydrate beverage (2%) or a concentrated carbohydrate beverage (12%) as a bolus equating to 7.5 $ml \cdot kg^{-1}$. The composition of the drinks is shown in Table 2. On average this equated to ingestion of 11.5g of carbohydrate for the 2% trial and 68.8g of carbohydrate for the 12% trial. The fluid consumed was delivered in a single blind randomized cross-over fashion and was ingested 30 minutes prior to the start of the high-intensity exercise capacity test. During the 30 minute rest period participants remained

in the laboratory and were fitted with a heart rate monitor (Polar Electro, Finland). Following the rest period, another blood sample was obtained and a further BRUMS questionnaire completed immediately prior to taking position on the cycle ergometer. Participants were given a 5 minute warm up at half of their 90% PPO workload and, after completion of the warm up, then cycled at 90% of PPO until volitional exhaustion. Heart rate was recorded throughout exercise and rating of perceived exertion (RPE, Borg, 1982) was recorded at 2 min, 5 min and at the end of exercise. Blood samples were obtained at 2 min and 5 min during exercise, then 3 min after reaching volitional exhaustion. No verbal encouragement or music was provided on any of the trials. A final BRUMS questionnaire was completed immediately following exercise. A schematic of the study protocol is shown in Figure 1. In all trials blood sample analyses for glucose and lactate were performed immediately upon collection using an Electrolyte Metabolite Laboratory analyser (EML105, Radiometer, Copenhagen).

Statistical analysis

In Part A and Part B baseline blood sample values from each experimental trial were compared using one-way ANOVA. Exercise capacity was analysed using Student's paired T-tests with Bonferroni correction. Metabolites, heart rate and mood/arousal scores were assessed using repeated measures ANOVA to determine trial, time, or trial x time interaction effects. Change in mood/arousal subscale scores between baseline and pre-exercise were assessed using one-way ANOVA. Pearson correlation analysis was used to examine associations between plasma glucose elevation and exercise capacity. All data are expressed as Mean (SD) or Mean (95% confidence interval) in the text and Tables, and as Mean (SEM) in Figures. Significance was accepted at $p<0.05$ or the Bonferroni adjusted value of $p<0.008$ for exercise capacity in Part A, and $p<0.016$ for exercise capacity in Part B.

RESULTS

All participants completed the trials and none had any side effects such as gastrointestinal distress from any of the drinks ingested.

Part A – Timing of intake

High-intensity exercise capacity was significantly influenced by timing of CHO ingestion. Ingestion of a 6.4% carbohydrate drink 30 minutes before exercise resulted in a significantly greater exercise capacity than all other trials ($P<0.008$, Figure 2A). The greatest mean (95% CI) difference in exercise capacity was between P30 and C30 trials with a 1.27 (0.72, 1.82) min improvement revealing the effect of carbohydrate feeding. However, there was a greater than 1 minute improvement in exercise capacity when comparing C30 vs. C120 trials (1.06 (0.63, 1.50) min) revealing the effect of timing of carbohydrate intake. There was no difference in exercise capacity between P30 and P120 trials (0.28 (-0.25, 0.80) min) and no difference between P120 and C120 trials (0.21 (-0.46, 0.87) min). This equates to a 17(4)% increase in exercise capacity on the C30 trial compared with the P30 trial, and a 14(3)% increase on C30 compared with the C120 trial.

Due to the timing differences in pre-exercise carbohydrate feeding in the study design there was, as expected, significant main effects of trial, time and an interaction (all $P<0.01$) for blood glucose. A higher pre-exercise plasma glucose concentration was observed on the C30 trial compared to all other trials (Figure 3) with no difference at baseline. Post-exercise plasma glucose was significantly lower on the C30 trial compared with P30 and P120 only. There was a significant but weak positive correlation between pre-exercise plasma glucose concentration and high intensity exercise capacity (r value of 0.26, $P=0.03$). No differences between trials and no interaction effects were observed with the plasma lactate data or heart rate response data (Figure 3).

Mood subscale scores did not reveal any significant trial, time or trial x time interactions with the exception of a time effect on the Fatigue subscale score. Fatigue rating was significantly higher post-exercise than baseline or pre-exercise values on all trials. Change in mood score between baseline and immediately pre-exercise revealed a significant effect for the Tension subscale. A higher mean (SD) tension change score was observed on P120 (0.41(0.71) units) compared with C30 (-0.29 (0.59) units) and C120 (-0.18(0.73) units) trials. Increase in mean (SD) vigour scores (1.18(1.85) units) and reduction in fatigue scores (-1.35(1.73) units) from pre-drink to pre-exercise were greatest on the C30 trial but did not reach significance when compared with other trials.

Part B – Carbohydrate concentration

High intensity exercise capacity was not significantly affected by the carbohydrate concentration ingested 30 minutes before exercise in Part B of the study (P=0.09; Figure 2B). However, the mean (95% CI) difference in exercise capacity between 0% and 2% trials was 1.01 (-0.12, 2.14) min, and between 12% and 2% trials was 1.13 (-0.10, 2.37) min. The difference between 0% and 12% trials was 0.12 (-0.55, 0.80) min. Thus, the magnitude of difference in exercise capacity between the 2% trial and the other trials was similar to that observed between C30 and the other trials in Part A of the study. The effect equates to a mean (SD) increase of 12(21)% in exercise capacity on the 2% trial compared with the 0% trial, and a 15(25)% increase from the 12% trial. Post-trial sample size calculations revealed that for 80% power with a pooled SD of 1.33 and a mean difference of 1.07 min a sample size of 13 would be required to detect a significant effect.

Due to the differing carbohydrate concentration of ingested drinks there were significant main effects of trial, time and trial x time for plasma glucose response (Figure 4). There was no

difference in baseline plasma glucose concentration but a higher pre-exercise plasma glucose concentration was observed on the 12% trial compared with 2% and 0% ($P<0.01$), and on the 2% trial compared with the 0% trial ($P<0.01$). These differences remained following 2 minutes of the high intensity exercise task but were not apparent when 5 minutes of exercise had been completed. No differences were noted between trials for post-exercise glucose concentration. No differences between trials and no interactions were observed for plasma lactate or heart rate responses to exercise (Figure 4). No differences in RPE were noted between trials but there was a significant time effect with RPE increasing from 15(2) at 2 min, to 18(1) at 5 min and to 20(0) at the point of exhaustion on all trials.

Mood subscale scores did not reveal any significant trial, time, or trial x time interactions. Change in mood score between baseline and immediately pre-exercise also did not reveal any significant differences between trials (data not shown).

DISCUSSION

The two parts of the present study have provided interesting new insights into a possible benefit of pre-exercise carbohydrate ingestion on high-intensity short duration exercise capacity. In Part A, the key observation was that high-intensity exercise capacity was significantly improved by ingestion of 32g of carbohydrate taken 30 minutes before exercise (14-17% increase), compared with ingestion of 32g of carbohydrate 2 hrs before exercise, or placebo solutions ingested 30 minutes or 2 hours before exercise. In Part B, a similar magnitude of change (12-15% increase) in exercise capacity, albeit not reaching statistical significance, was observed over 0% and 12% pre-exercise carbohydrate ingestion trials when a 2% carbohydrate solution was ingested 30 minutes before exercise. These combined observations from Part A and Part B suggest there is an optimal timing of ingested carbohydrate for short duration high-intensity exercise tasks lasting <10 minutes, but more work is required to determine whether there is an

optimal concentration. These observations also require more detailed mechanistic exploration in future studies.

Part A - Timing of carbohydrate intake

Research on the metabolic effects of pre-exercise carbohydrate feeding has usually been confined to examination of effects on prolonged endurance exercise tasks. Many studies have adopted a fixed workload exercise period followed by a performance task (Moseley et al., 2003; Jentjens et al., 2003), or have examined prolonged continuous or intermittent endurance tasks (Pritchett et al., 2008). The fixed workload period in these studies has revealed that metabolic disturbances from carbohydrate feeding are short-lived and typically only remain evident during the first 10-15 minutes of prolonged activity when carbohydrate is ingested 15-30 minutes prior to exercise, and are often not evident at all if carbohydrate is ingested 75-120 minutes before exercise. Other studies also reveal that there is an accelerated glucose uptake/oxidation by contracting skeletal muscle in the early stages of exercise when pre-exercise blood glucose concentration is elevated (Febbraio et al., 2000a,b; Tsintzas et al., 2000). To date, there have been no investigations specifically exploring the potential for these metabolic disturbances, induced by pre-exercise carbohydrate feeding, to benefit high-intensity exercise capacity. In particular, during exercise tasks that last only as long as the metabolic disturbance itself, it may be possible to maximize glucose uptake / oxidation in the early stages of exercise, and positively influence high-intensity exercise capacity

The greater exercise capacity noted in the present study when carbohydrate was ingested 30 minutes before exercise would initially appear to support the hypothesis that elevated pre-exercise glucose benefits high-intensity exercise tasks. Indeed, it is likely that plasma insulin would also be elevated immediately pre-exercise on the C30 trial. The combined effect of high insulin and high glucose before exercise would act to blunt the mobilization and oxidation of

fatty acids (Bonen et al., 1981) and would push metabolism towards increased carbohydrate oxidation by blunting hormone sensitive lipase activity and activating the pyruvate dehydrogenase enzyme complex (Watt et al., 2004; Tsintzas et al., 2000). In high intensity efforts lasting only 8-10 minutes there is still a significant aerobic component, and an increased flux through glycolysis in the early stages of exercise would aid metabolic integration/regulation i.e. better matching of ATP supply with demand for ATP (Timmons et al., 1998). Indeed, Timmons et al. (1998) demonstrated that activation of the pyruvate dehydrogenase enzyme complex (PDC) with dichloroacetate improves fatigue resistance in a single leg ischaemic exercise model. These previous studies provide a clear metabolic explanation for the current findings of improved exercise capacity in the present study, and the lower post-exercise glucose concentration noted in the C30 trial of the present study may provide some indirect evidence to support greater glucose uptake and oxidation, but this may not be the whole answer.

The improvement in exercise capacity observed in the present work was not convincingly associated with the pre-exercise plasma glucose concentration, or a change in concentration from pre-drink to pre-exercise. It is also worth considering that the effect of enhanced glucose uptake and oxidation in non-ischaemic contracting muscle is likely to be small, and it could be argued that the lower plasma glucose concentration following exercise just reflects the longer total exercise duration on that trial. Therefore, other explanations for the enhanced exercise capacity should be considered. In the present study the participants were overnight fasted. Although liver glycogen stores would not be fully depleted on entry to the laboratory (Casey et al., 2000) feeding of carbohydrate on the C30 and C120 trials might be expected to contribute to liver glycogen stores. It is also probable that the elevation in liver glycogen content would be greater on the C120 trial due to the expected time course of storage (Casey et al., 2000). This would suggest that differences in liver glycogen content are not playing a key role in influencing high-intensity exercise capacity in the present study, although further investigation is necessary

before this can be ruled out. Another factor worth considering is the impact of the seated rest period on the exercise capacity outcome. It may have been prudent to have participants seated for 90 minutes before the ingestion of carbohydrate or placebo in the C30 and P30 trials. However, the lack of any difference in exercise capacity between P30 and P120 trials would suggest that any impact of seated rest duration is likely to be small.

These preliminary observations suggest that metabolic factors probably have a part to play in the enhanced exercise capacity on the C30 trial, but other non-metabolic explanations should also be considered. It is possible that a positive temporal mood/arousal alteration to feeding of carbohydrate (increased vigour, decreased fatigue) would occur when carbohydrate was ingested 30 minutes before exercise, and that a potentially negative mood/arousal alteration (increased fatigue) would occur when carbohydrate was ingested 2 hr before exercise (Benton and Owens, 1993, Berridge and Robinson, 1998; Benton, 2002). However, the data obtained in the present study do not support this hypothesis, but may be limited by the sensitivity of the methodological approach. It is also possible that the positive exercise capacity outcome observed on the C30 trial is linked to other central neural effects of carbohydrate feeding, possibly including oral sensing of carbohydrate ingestion and altered neuromuscular control (Rollo et al., 2010; Chambers et al., 2009; Carter et al., 2004; Lambert et al., 2005; Gant et al., 2010). However, there are considerable differences between the mouth rinse literature and our current experimental approach, not least of which is the exercise intensity and duration. The mouth rinsing studies typically examine performance tasks lasting around 1 hour, and the magnitude of positive effect is in the region of 1-4%. This contrasts to our use of a short duration high intensity exercise capacity test, but we have observed moderate positive improvements of around 15% which could also be expected to translate to a performance improvement in the region of 1-4%. Since mouth rinsing is usually conducted during the warm-up phase in the previous protocols and mainly uses drinks containing around 6% carbohydrates, it would seem

prudent to apply these methods to investigate mechanisms for enhanced exercise capacity/performance with carbohydrate feeding in future high-intensity exercise studies.

Part B – Carbohydrate concentration

Given that timing of carbohydrate intake appears important and that it likely reflects both metabolic and neural effects of carbohydrate ingestion, there may also be an optimal dose effect of carbohydrate for high-intensity short-duration exercise capacity tasks. In Part B of the study, although we did not observe a statistically significant effect of carbohydrate concentration on exercise capacity, we have provided some evidence for a concentration mediated effect. Exercise capacity was similar on all (0%, 2% and 12%) trials. The non-significant increase in exercise capacity on the 2% trial suggests further work should be done with larger sample sizes.

Previous work has shown a dose-response relationship between glucose feeding and central cognitive function tasks in older adults (Parsons and Gold, 1992). Enhanced memory following glucose ingestion, compared with placebo, occurred when 25g of glucose was ingested but not when 10g or 50g of glucose was ingested. This inverse U type effect of glucose on cognitive function tasks has also been demonstrated in animal models and in other human studies (Gold, 1995). If these concepts were to hold true for effects on centrally driven improvements in exercise capacity then there could be an optimal carbohydrate concentration for maximizing high-intensity exercise capacity or performance. Given the observations of Parsons and Gold (1992) and others, it is likely that we may have missed the optimal concentration of carbohydrate in the present study since our participants ingested on average 0g, 11.5g and 68.8g of carbohydrate prior to each exercise trial. It may be that ingestion of a 4-6% solution which would have provided around 24-34g of carbohydrate might have been closer to an optimal dose for metabolic and central neural effects. The 6.4% solution providing 32g of carbohydrate in Part A of our study demonstrated a significant impact upon exercise capacity,

and therefore may indirectly provide some evidence to support a dose-response. However, this observation needs to be assessed within a single study protocol to confirm this assertion.

Interestingly, McConnell et al. (1996) examined the effects of carbohydrate feeding and blood glucose elevation in the last 30 minutes of a 2 hour cycle ride on a subsequent 15 minute high-intensity exercise performance task. In their study, participants ingested either placebo (0% CHO) or a 7% CHO solution throughout the 2 hour ride, or ingested placebo for 90 min followed by a 21% CHO solution in the final 30 minutes. Not surprisingly, blood glucose concentration at the end of the 2 hour ride was highest in the trial where the 21% solution was ingested, was intermediate with the 7% and lowest with the 0% solutions. No difference in total amount of work performed in 15 minutes was observed between 0% (242(9) KJ) and 21% (253(10) KJ) trials, but total work performed was greater in the 7% trial (268(8) KJ). These data appear to add to the notion that there may be an optimal drink concentration prior to high-intensity exercise tasks.

Our observations of a clear timing of intake effect, and the suggestion of a dose-response effect, provide a sound basis from which to more fully investigate pre-exercise carbohydrate feeding strategies for high-intensity exercise capacity. The potential translation to exercise performance and practical guidance for athletes requires further study focusing on central neural, metabolic, or peripheral neuromuscular control mechanisms.

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483

484 **DECLARATION OF FUNDING SOURCES AND CONFLICT OF INTEREST**

485 This project was supported by University of Stirling, School of Sport. SDRG has received
486 support for research from sport drink manufacturers in the past but none were involved in
487 funding or supporting the present work.

488

FIGURE LEGENDS.

Figure 1: Study design schematic diagrams detailing the experimental trial protocols for Part A (timing of intake) and Part B (concentration of carbohydrate) sections of the study.

Figure 2. Mean (SEM) high-intensity exercise capacity following ingestion of carbohydrate or placebo 30 minutes (C30, P30) or 2 hrs (C120, P120) before exercise in Part A (A), and following ingestion of 0%, 2% and 12% carbohydrate solutions 30 minutes before exercise in Part B (B). a, b, d – indicate a significant difference from trials P30, P120, and C120, respectively.

Figure 3: Mean (SEM) plasma glucose concentration, plasma lactate concentration and heart rate during exercise following ingestion of carbohydrate or placebo 30 minutes (C30, P30) or 2 hrs (C120, P120) before exercise in Part A of the study. a, b, d – indicate a significant difference from trials P30, P120, and C120, respectively.

Figure 4: Mean (SEM) plasma glucose concentration, plasma lactate concentration and heart rate during exercise following ingestion of carbohydrate or placebo 30 minutes (C30, P30) or 2 hrs (C120, P120) before exercise in Part B of the study. a, b, c – indicate a significant difference from trials 0%, 2% and 12%, respectively.

506 **Table 1**: Mean (SD) participant characteristics obtained on the initial laboratory visit for Part A
507 (timing of carbohydrate intake study) and Part B (concentration of carbohydrate intake study).

	Part A	**Part B**
n	17	10
Age (yr)	23.6 (4.8)	21.2 (0.8)
Height (m)	181.6 (6.4)	179.1 (4.9)
Mass (kg)	75.5 (6.9)	76.4 (5.0)
Peak power output (W)	270 (32)	312 (23)

508

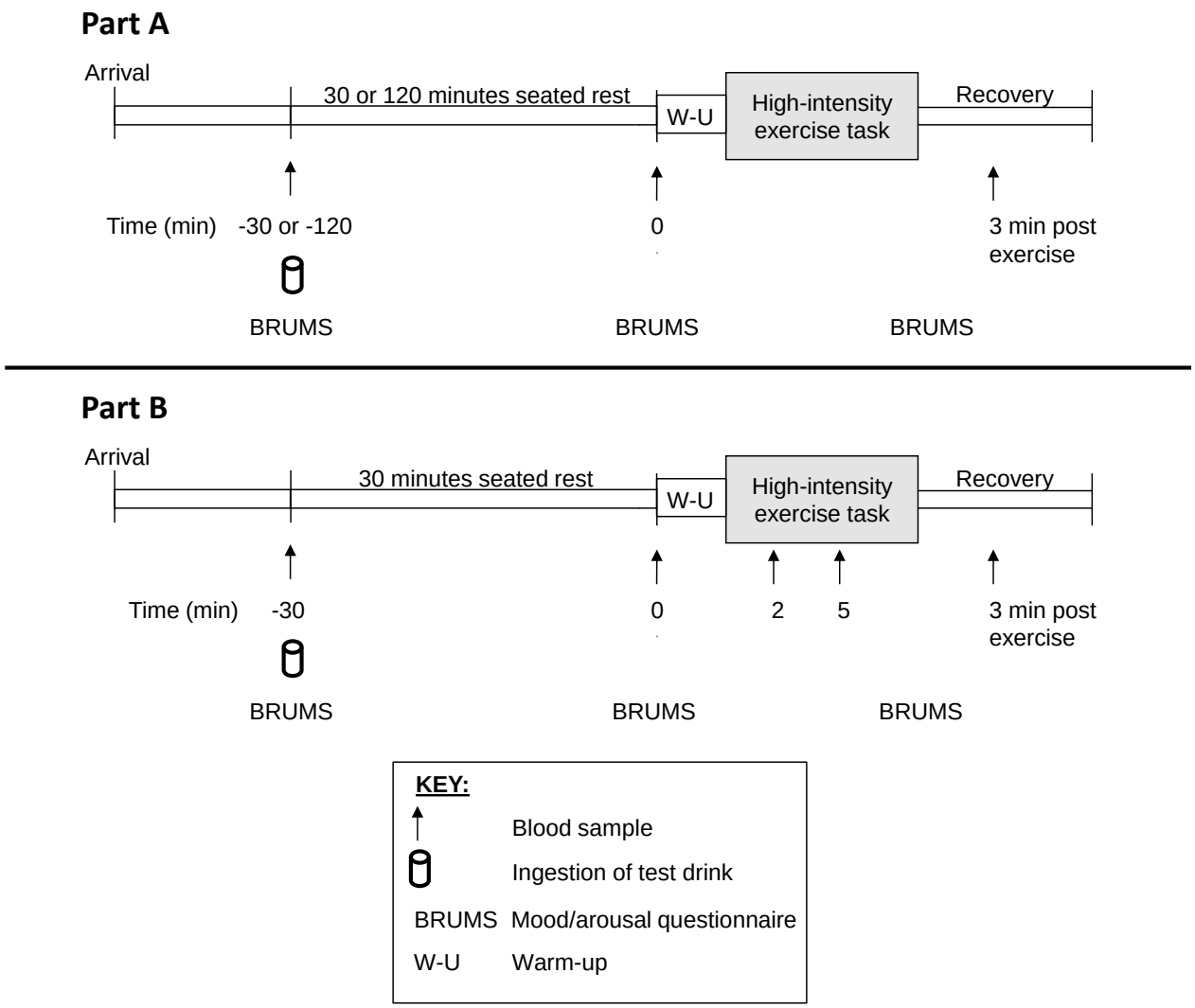
509 **Table 2**: Composition of the drinks ingested in Part A (timing of carbohydrate intake study) and
510 Part B (concentration of carbohydrate intake study).

	Part A	**Part B**
0% drink	Colour and flavour matched water	Colour and flavour matched water
2% drink	-	20 g/L glucose solution with low calorie flavouring
6.4% drink	64 g/L commercially available carbohydrate/electrolyte drink (24mM Na^+)	-
12% drink	-	120 g/L glucose/maltodextrin solution with low calorie flavouring

511

512 **Figure 1.**

513



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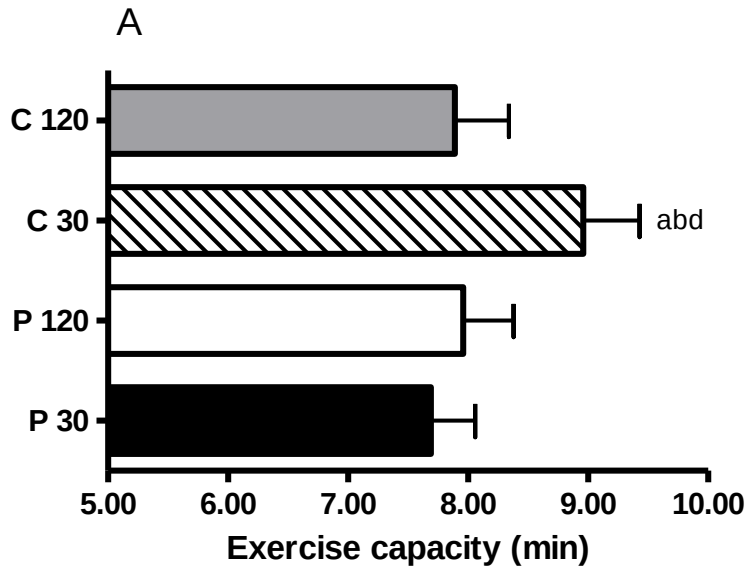
516 **Figure 2**.



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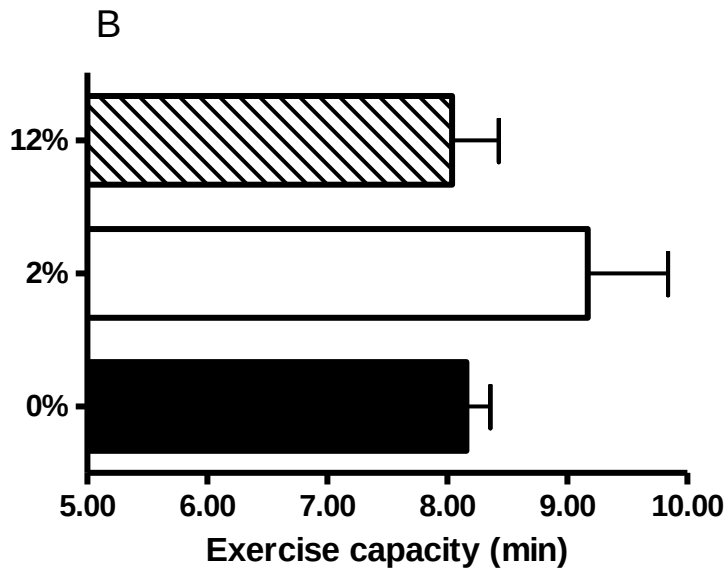

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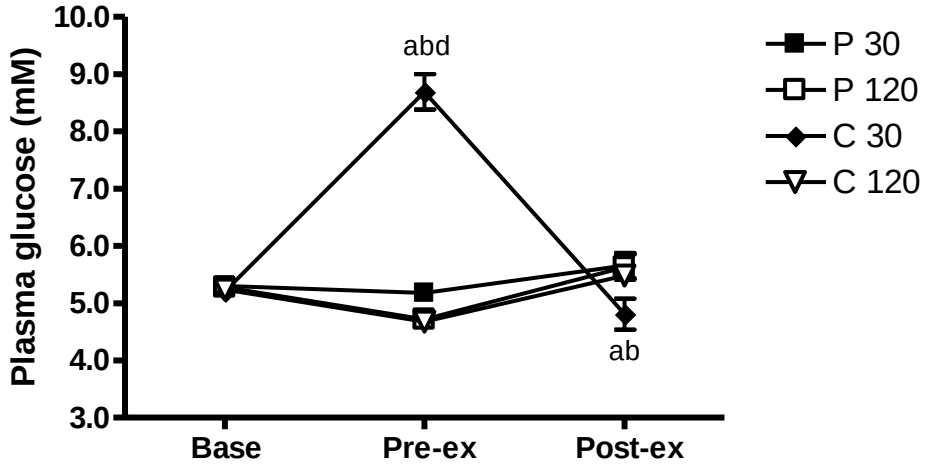

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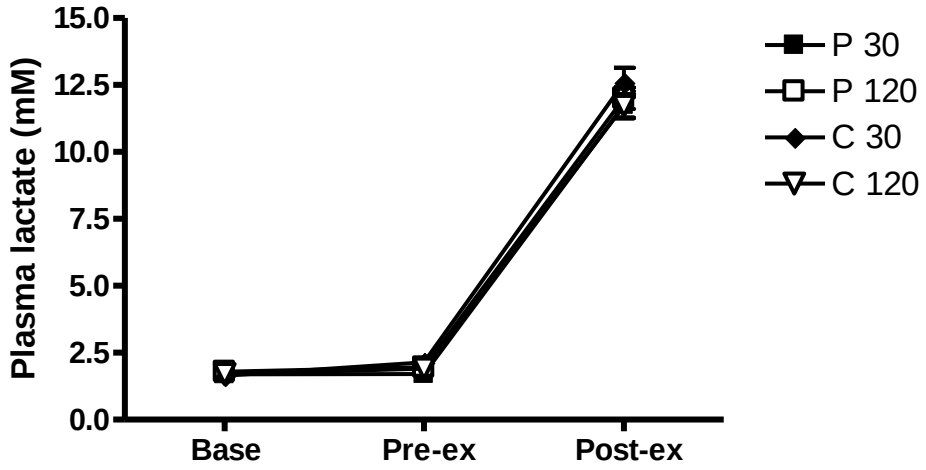

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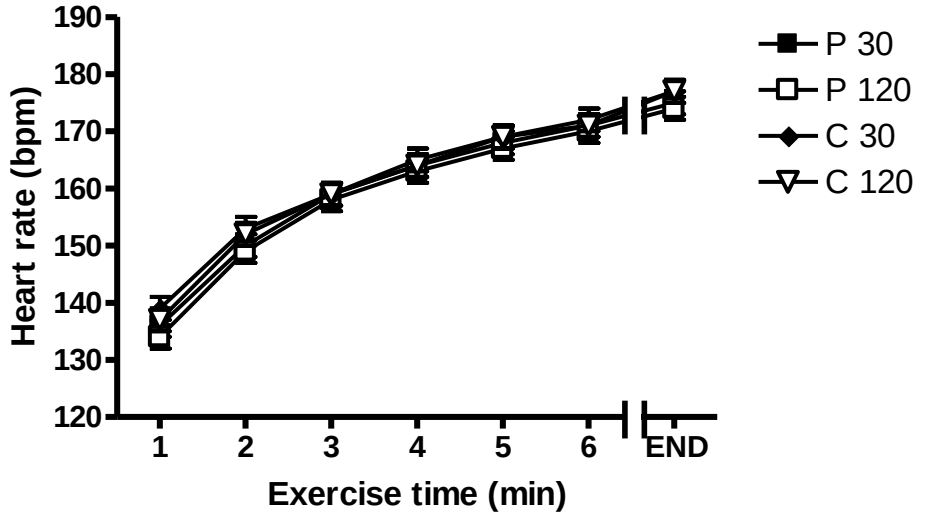

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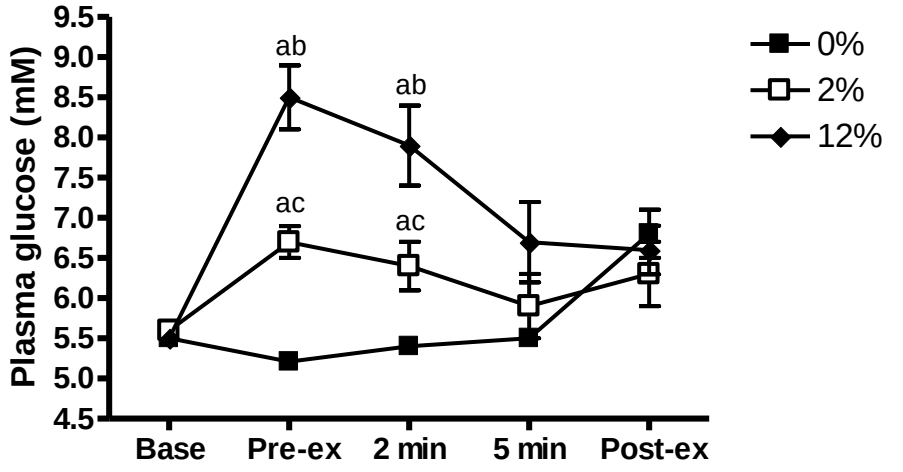
524 **Figure 4.**



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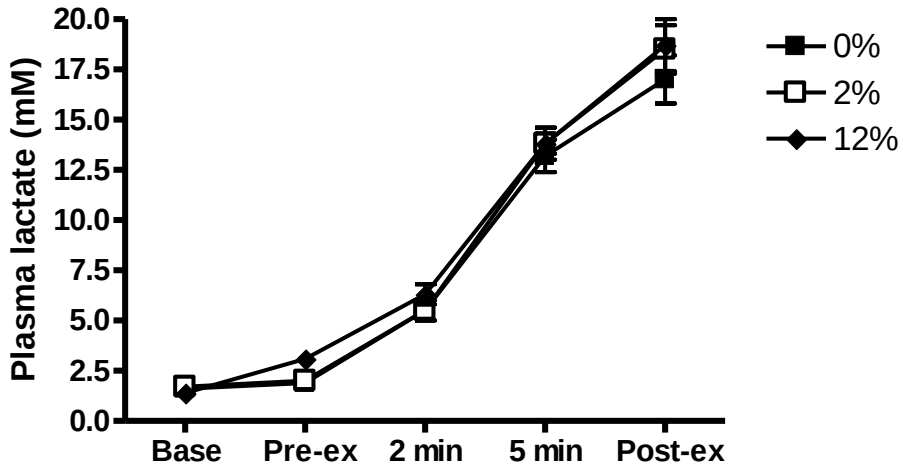

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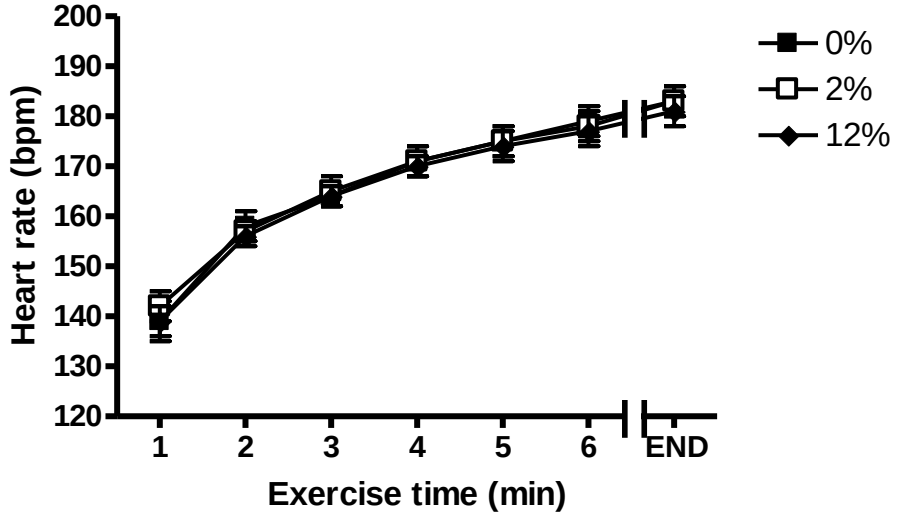

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