

## **Effect of Carbohydrate Intake on Half-Marathon Performance of Well-Trained Runners**

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Eighteen highly-trained runners ran two half marathons in mild environmental conditions, 3 wk apart, consuming either 426 ± 227 mL of a flavored placebo drink (PLACEBO) or an equivalent volume of water (386 ± 185 mL) and a commercial gel (GEL) supplying 1.1 ± 0.2 g/kg body mass (BM) carbohydrate (CHO). Voluntary consumption of this fluid was associated with a mean BM change of ~ 2.4%. Runners performed better in their second race by 0.9% or 40 s ( $P = 0.03$ ). Three runners complained of gastrointestinal discomfort in GEL trial, which produced a clear impairment of half-marathon performance by 2.4% or 105 s ( $P = 0.03$ ). The effect of GEL on performance was trivial: time was improved by 0.3% or 14 s compared with PLACEBO ( $P = 0.52$ ). Consuming the gel was associated with a 2.4% slower time through the 2 × 200 m feed zone; adding a trivial ~ 2 s to race time. Although benefits to half marathon performance were not detected, the theoretical improvement during 1-h exercise with CHO intake merits further investigation.

**Key Words:** exogenous CHO, elite athletes, one-hour performance

There is evidence that the intake of carbohydrate (CHO) immediately before and during high-intensity exercise is of benefit to performance, independently of its effects on muscle fuel status. Several studies involving cycling protocols have shown that CHO intake enhances performance of a high intensity exercise task of ~ 1 h duration, compared to water or an artificially sweetened placebo (4, 6, 18). In these situations muscle glycogen stores are not considered to be limiting, especially if the athlete has “fuelled up” prior to the event (14). Instead, a number of investigators speculate that CHO intake exerts a favorable effect on sensory input to the central nervous system (6, 7).

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Although the literature on the effects of CHO supplementation on exercise lasting ~ 1 h is growing, only two investigations to date have employed a running protocol (21, 27). In one study, well-trained runners ran for 13.4 km at a steady-state on a laboratory treadmill, before completing the 15 km protocol with a 1.6 km time trial (TT). The performance of this TT was significantly faster after runners consumed either a 6 or 8% CHO-electrolyte drink, compared with an artificially sweetened placebo (21). During real-life competition, however, we and others (25) have observed that competitive distance runners do not drink the volumes of fluid typically consumed in experimentally controlled studies. In addition to cultural factors underpinning the nutrition beliefs and practices of distance runners, there are significant practical factors that limit intake during running events. For example, the runner has to slow down to obtain and consume a beverage at aid stations. This action causes an immediate reduction in race pace, but might also interrupt race rhythm and provide other competitors with the opportunity for strategic race tactics (e.g., surging away while the runner is distracted). In addition, there is a potential for gastrointestinal discomfort/upset arising from the intake of fluid or CHO while undertaking high-intensity exercise of a “joggling” nature (5).

Despite the proposed benefits of replacing fluid losses during exercise to minimize the accruing fluid deficit caused by sweat loss (1), the consumption of large volumes of fluid is often difficult for elite athletes running at high relative and absolute speeds. The use of sports gels (concentrated carbohydrate solutions) in conjunction with the intake of smaller volumes of fluid could, however, allow the runner to consume substantial amounts of CHO (e.g.,  $1 \text{ g}^{-1} \cdot \text{kg}^{-1} \cdot \text{h}^{-1}$ ) during marathon and half-marathon races, and presumably obtain the purported benefits of CHO intake during endurance events (> 90 min). This practice could also be beneficial for CHO replacement in shorter events (~ 1 h duration).

The aim of this study was to investigate the use of sports gels to achieve significant carbohydrate intake before and during a half marathon race. We aimed to build on the results of the sole study of CHO intake and 1 h running performance (21) in three key ways: first, to conduct our investigation as a field study to mimic real-life challenges such as consuming fluids and other supplies from aid stations, and to allow effects on race pacing strategies to be observed; second, to study runners of a higher caliber, and therefore, higher absolute running speed, so that the challenges of obtaining supplies during a race and the risk of gastrointestinal discomfort during the race were increased; and finally, to determine the magnitude of the effect of the intake of gel on total running time for the half marathon, the time lost in consuming the gel during the race, and the incidence of gastrointestinal problems.

## Methods

### Overview

The investigation was undertaken as a field study involving two separate groups of subjects who each undertook two half-marathons in a cross-over designed protocol. Because it was impossible to provide an energy-free product indistinguishable from a commercial sports gel, the placebo used in this study was an artificially sweetened drink. Runners were told that the intention of the study was to compare running performances while consuming either a sports drink or sports gels before and during

the race. The study was approved by the Ethics Committee of the Australian Institute of Sport (AIS), and all runners provided signed informed consent after having the details and risks associated with the study explained to them.

## Subjects

Twenty highly-trained male distance runners, with an actual or predicted half marathon time of 75 min or less, were recruited from a local pool via newsletters and contact with running clubs. Groups 1 and 2 consisted of 10 and 8 runners, respectively. The recruitment process offered these athletes the opportunity to undertake the 2 races, 3 wk apart, over an accredited (officially measured) course. Prize money was offered for the average race time under a handicap system based on predicted finishing time to provide each runner with motivation to run as hard as possible in both races. Subjects attended the laboratory of the Department of Physiology at the AIS to undergo baseline testing of fitness and training characteristics and to receive full instruction about the study and the race course.

Maximal oxygen uptake ( $\text{VO}_{2\text{max}}$ ) was determined during an incremental test to volitional exhaustion on a custom-built motorized treadmill (Australian Institute of Sport, Belconnen, Australia) at an ambient temperature of 20 to 22 °C. The protocol involved subjects running at three set running speeds (14, 16, and 18 km/h; 0% grade) for 4 min; at the completion of each 4 min stage the treadmill was stopped for 1 min. Subjects were then required to perform an incremental protocol starting at 18 km/h and increasing by 1 km/h every minute up until 20 km/h. Once this speed was attained the treadmill gradient was increased by 1% every minute until volitional exhaustion was reached. An in-house automated metabolic system was used to calculate  $\dot{V}_E$ ,  $\text{VO}_2$ , and RER. The  $\text{VO}_{2\text{max}}$  was determined as the  $\text{VO}_2$  beyond which further increases in  $\text{VO}_2$  were not made, despite increased exercise intensity. The typical error of measurement for  $\text{VO}_{2\text{max}}$  measured in our laboratory is 2.2%.

Eighteen of the runners completed both races; two runners from the second cohort were unable to undertake their second race due to illness (1 runner) and injury (1 runner). These subjects have been excluded from all further representation in this article; the characteristics of the 18 subjects who finished the study are presented in Table 1.

## Preparation for Races

A half-marathon (21.1 km) course was officially measured by a representative of the Australian Capital Territory Cross Country Running Club in accordance with

**Table 1** Characteristics of Runners Who Completed the Study ( $n = 18$ )

Characteristic	Mean $\pm$ SD
Body mass (kg)	66.4 $\pm$ 6.3
$\text{VO}_{2\text{peak}}$ ( $\text{mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ )	71.1 $\pm$ 3.8
Predicted or actual best time for half marathon (min)	71.2 $\pm$ 3.3

procedures that would allow the event to be sanctioned by Athletics Australia, the national governing body of distance running in Australia. The course was situated in a relatively sheltered location and involved ~ 3 laps of a pathway surrounding a lake; these characteristics were chosen to minimize the impact of weather conditions, such as wind. The races were conducted during early spring, when constant and temperate weather was expected. Environmental conditions (temperature, humidity, and wind speed) were measured using a Kestrel 4000 temperature monitor (Nielsen-Kellerman, Boothwyn, PA) just before the commencement, mid point, and the end of each race.

The two half-marathon races were held 3 wk apart to allow for full recovery between events. Runners were asked to prepare for each half-marathon with a standardized week of training and pre-race taper. Dietary preparation was standardized by providing each runner with a meal pack for the day before the race [providing 8 g of carbohydrate per kilogram of body mass (BM)] and for the pre-race meal (1 g CHO/kg BM). Logs of training and food intake were kept, and examined on the morning of the second race, to ensure that each runner had undertaken the same preparation for each of his races and consumed the required food, including the pre-race meal. Once compliance with food and training had been established, runners were instructed to undertake their pre-race warm-up; this was individualized to each runner but standardized for both races.

### **Race Protocol (Including Warm-Up)**

During the 30 min prior to each race, runners were provided with a drink bottle containing the treatment drink for that trial, with instructions to consume the drink during their warm-up and race preparation. Ten minutes prior to race start, runners undertaking the GEL trial were provided with their first sports gel allocation and supervised while consuming it. During the final minute before the start of the race, runners assembled at the race start. A 25  $\mu$ L blood sample was taken from the fingertip of each subject and placed on ice for subsequent determination of glucose and lactate concentrations using an automated method (EML-105, Radiometer, Copenhagen, Denmark). Body mass was recorded on Precision Health Scales UC 300 (A & D Co., Ltd., Tokyo, Japan).

The representative from the ACT Cross Country Club started each race and provided official time-keeping duties throughout. This official was kept blind to the purpose of the study and to the allocation of treatments to each runner. Such involvement ensured that race times were accurate and unbiased by the researchers; furthermore, runners received the additional motivation of knowing that performances would be recognized by the national governing body of Athletics Australia. Measured zones of 200 m were set up at ~ 7 km and ~ 14 km into the race to encompass the area in which runners were required to obtain and consume their race fluids. Two tripod-mounted digital cameras were set up to monitor running time and activity in this “feed zone.” Given that any performance differences between treatments would likely manifest over the last 25% of the race, feedback of runners’ split times were provided at 5, 10, and 15 km distances for both trials. Official finishing times were provided on completion in the first race, but were kept hidden during the second trial until a post-race questionnaire had been undertaken. When runners crossed the finish line, a second blood sample was taken immediately

for determination of blood glucose and lactate concentrations, and body mass re-measured to determine the magnitude of change during the race. After completing these activities after the second race, runners completed a questionnaire that asked them to nominate in which trial they had performed better and the basis of their decision. They were also asked to recall if any gastrointestinal problems had occurred in either trial. Finally, they were asked to consider whether they would use sports gels in future races.

## Race Treatments

Runners received fluid to consume during the 30 min prior to the race (warm-up and preparation) and at two feed zones (7 km and 14 km) during the half-marathon. The fluids received were water (GEL trial) or an energy-free drink artificially flavored to taste like a sports drink (PLACEBO trial). The protocol was devised to ensure that the volumes consumed by each runner were similar to their usual race plan and matched for each of their trials. Fluids consumed before each race were provided in standard opaque drink bottles, while fluids provided during the race were taken from the feed zone in small plastic “squeeze bottles” specially manufactured to allow carriage and rapid consumption of the contents. Each bottle was labeled with the runner’s name and collected from the race start or feed zone after the runner had discarded it. The mass of bottles was recorded pre- and post-consumption to estimate the volume of fluid consumed at each time point. During each runner’s first trial, the drink bottle provided before the race contained 750 mL of their treatment fluid: the runner was instructed that he could drink as little or as much of this fluid as desired during the warm-up and pre-race period. On their subsequent trial, each runner received the opposite beverage in a volume that was identical to that consumed before the first race. On this trial, runners were instructed that they needed to consume the entire volume of fluid provided in their pre-race bottle. A similar protocol was followed with the drink bottles provided in the feed zones; in this case, the original volume of fluid provided was 150 mL per drink station. These original volumes of fluids were chosen after consultation with the runners to ascertain the maximum volume of fluid they were likely to consume in a real-life race.

The carbohydrate gel used in this study was a commercially available sports product provided in a plastic pouch (41 g) with a rip-top opening (Powergel, Nestle, Australia). A protocol was devised to ensure that each runner consumed sufficient gel to provide a carbohydrate intake equal to 1 g/kg BM immediately before and during the half-marathon. Each runner ran the race with two gel pouches pinned or taped to the inside of their running shorts. This method was chosen because it allows body temperature to keep the gel warm, making it softer and easier to consume, and because it mimics the real life practices of some triathletes and cyclists (personal observations). The race instructions were to consume as much gel as could be swallowed from one package at the start of each feed zone at 7 and 14 km, before ingesting the race drink. Pilot testing showed that it would be feasible for runners to consume about 30 g of gel from a gel pouch (~ 20 g of CHO) at each of the feed zones. Therefore, the pre-race gel provision was manipulated to make up the balance of a 1 g/kg CHO serve. Each gel package was labeled with the name of the subject so that discarded packages could be retrieved and weighed to estimate the actual CHO intake achieved by each subject.

## Statistical Analysis

Because identical protocols were followed in all of the races, the results of the dependent variables from the two groups ( $n = 10$  and  $n = 8$ ) were pooled. Paired *t*-tests were used to compare results between GEL and PLACEBO trials for the 18 runners for fluid intake and changes in body mass over the race. Pre- and post-race concentrations of blood glucose and lactate during the two trials were compared using a two-factor (trial and time) analysis of variance (ANOVA) with repeated measures. The Newman-Keuls post hoc test was undertaken when ANOVA revealed a significant interaction. These statistical analyses were undertaken using Statistica software for Windows (StatSoft, Inc., version 5.1, Tulsa, OK). The data are reported as mean  $\pm$  standard deviation.

The results of the performance variables investigated in this study (race time and time spent in the feed zones) were analyzed using mixed modeling for fixed and random effects. The fixed effects were the order of trials and the allocation of treatment group (GEL or PLACEBO). The random effects included performance time from trial to trial and the presence of gastrointestinal problems. Measurement of variability or standard error of measurement in performance time was calculated as the standard deviation of the change score divided by  $\sqrt{2}$ , within a test-retest design using the same subjects in two different trials (15).

This part of the analysis was conducted with Proc Mix in the SAS version 8.2 software package (SAS Institute, Cary, NC). Confidence intervals (90%) were calculated to indicate the precision of estimation of the size of the (unknown) true effect. We also estimated the likely clinical (practical) effect of CHO intake in terms of how it would change the outcome of a real race (16).

## Results

### Race Environmental Conditions

Each runner completed two races in similar environmental conditions. For the first group, race conditions ranged from 12 to 15 °C, 41 to 48% humidity, and wind speeds of 1.5 to 4 m/s over the hour duration of race one, while the range in conditions in race two were 9 to 11 °C, 43 to 46% humidity, and 1 to 3.5 m/s winds. For the second group of runners, race 1 conditions ranged from 16 to 21 °C, 32 to 47% humidity, and 1 to 1.5 m/s wind speed, and race 2 from 15 to 17 °C, 26 to 28% humidity, and 1 m/s winds. Examination of the training and food logs on the morning of each race showed that each runner was compliant to the standardized training and dietary protocol.

### Fluid Consumption and Physiological Changes

The characteristics of fluid and CHO intake achieved during each trial, and effects of these treatments on changes in body mass and blood concentrations of glucose and lactate are summarized in Table 2. Subjects consumed similar amounts of fluid in each of their trials;  $386 \pm 185$  mL in the GEL trial (mean intakes of 207 mL during the pre-race period, 92 mL in feed zone 1, and 86 mL in feed zone 2) and  $426 \pm 227$  mL in the PLACEBO trial (mean intakes of 236 mL during the pre-race period,

**Table 2 Race Characteristics**

Characteristic	GEL trial	PLACEBO trial
Total fluid consumed pre-race and during race (mL)	386 ± 185	426 ± 227
CHO consumed immediately before and during race (g)	1.1 ± 0.2	0
Body mass loss during race (kg)	1.5 ± 0.3	1.7 ± 0.5
Blood glucose concentration (mmol/L)		
pre-race	5.8 ± 0.6	5.2 ± 0.7
post race	8.8 ± 2.9*	7.2 ± 2.8*
Blood lactate concentration (mmol/L)		
pre-race	1.8 ± 0.5	1.5 ± 0.4
post race	10.0 ± 2.7*	8.8 ± 3.4*

Note. Values are means ± standard deviation for  $n = 18$  subjects; \*post-race > pre-race ( $P < 0.05$ ).

97 mL in feed zone 1, and 93 mL in feed zone 2). A loss of body mass of  $1.5 \pm 0.3$  kg and  $1.7 \pm 0.5$  kg was observed in the GEL and PLACEBO trials, respectively (NS), suggesting that a fluid deficit of  $\sim 2.4\%$  BM was incurred in both trials. The mean intake of CHO achieved in the GEL trial was 66 g, equivalent to  $1.1 \pm 0.2$ g/kg BM. Concentrations of blood glucose and lactate were elevated at the end of the half marathon compared to pre-race concentrations (see Table 2). There were no differences between the GEL and PLACEBO trials, however.

## Performance Outcomes

Table 3 summarizes the analysis of race performances, including total time to complete the half marathon, and time to run through the feed zones. Overall, the variability of half-marathon race time was 1.1%. There was a substantial order effect on total race performance: runners performed better in their second trial by 0.9%, equivalent to an improvement of 40 s over the half-marathon distance. Split times for each of the five segments of the race revealed that pacing differences between the races undertaken with different treatments were trivial (data not shown). Seventeen of the eighteen runners were able to correctly nominate the trial in which they performed best, based on their perceptions of effort and knowledge of their splits during the earlier part of the race. The post-race questionnaire revealed that three runners complained of some gastrointestinal discomfort in the GEL trial. The presence of gastrointestinal symptoms was associated with a substantial impairment of half-marathon performance, increasing overall race time by 2.4% or 105 s. The mean improvement in half marathon time in runners using the sports gel (GEL) compared with the PLACEBO trial was a trivial 0.3% ( $P = 0.52$ ). During the GEL trial, however, there was a strong trend for a slower running time through the 2 ×

**Table 3 Race Performance Results**

Characteristic	Comparison	Mean time	Mean effect*		P-value
			(%)	90% CI	
Total race time	Trial order	1	73.79 min	+ 0.9	0.03
		2	73.12 min	0.2 to 1.6	
	Treatment	Placebo	73.56 min	+ 0.3	0.52
		Gel	73.35 min	-0.7 to 1.0	
	Gastrointestinal discomfort	No	72.58 min	- 2.4	0.04
		Yes	74.33 min	-4.1 to -0.6	
Time through the feed zones (2 × 200 m zones)	Trial order	1	85.9 s	+ 1.0	0.40
		2	85.1 s	-1.0 to 3.1	
	Treatment	Placebo	84.5 s	- 2.4	0.08
		Gel	86.5 s	0.1 to 4.7	
	Gastrointestinal discomfort	No	82.5 s	- 6.9	0.03
		Yes	88.6 s	-11.5 to -2.0	

*Note.* \*denotes difference between first and second condition; +ve value means that second condition enhanced performance compared with first condition.

200 m feed zone, increasing the time spent in this zone by 2.4% or 2 s ( $P = 0.08$ ). Sixteen of the runners, including all runners who had experienced gastrointestinal problems, stated that they would like to use gels in future races, including half-marathons and marathon races, particularly following an opportunity for further practice and experimentation.

## Discussion

In this field study, eighteen highly-trained runners competed in two half-marathon races under standardized conditions of pre-race training and diet. We found that the use of a sports gel immediately before and during the race only elicited a trivial effect on overall race performance and pacing strategies, with the mean change in half-marathon time being a ~ 14 s improvement. Although this might seem a useful outcome for some high-level half-marathons in which place-getters finish within seconds of each other, within-athlete variation in performance must

be considered as well as between-athlete differences. According to Hopkins et al. (16), simulations of athletic events show that the smallest worthwhile enhancement of performance for an athlete in an international event is 0.7 to 0.4 of the typical within-athlete random variation in performance between events. Therefore, our mean improvement of 0.3% is below the range that would be useful in this group of runners with a performance coefficient of variation of 1.1%, or other competitive male half-marathon runners with a reported variation in performance of  $\sim 2.5\%$  (17). The intake of a gel during the race increased running time during the feed zone, compared with the intake of a small amount of fluid alone, adding an extra 2 s to total race time. Although this change approached statistical significance, the total effect on race time is trivial in clinical or practical terms. In a small number of runners, the intake of the gel was associated with gastrointestinal problems, which produced a clear impairment of running performance by a mean of 105 s. Despite the absence of a clear enhancement of running performance, the majority of runners stated that they would consume gels in future distance running races. This position represents a major change to their habitual race nutrition strategies that normally involve the intake of small volumes of fluid and no (half-marathon) or little (marathon) intake of CHO.

Our findings are in agreement with some studies (11, 19, 27), but contradict the results of other investigations in which the intake of CHO immediately before and during a high-intensity protocol lasting  $\sim 1$  h produced a worthwhile or statistically significant improvement in exercise capacity or performance (3, 4, 6, 18, 21, 22, 24). The characteristics of these studies are summarized in Table 4 to identify factors in the study protocols that might explain the apparent inconsistency in the literature. Before these factors can be considered, however, it is important to identify mechanisms by which CHO intake might enhance the capacity for sustained exercise undertaken at a workload of  $\sim 75$  to 85% of  $\text{VO}_{2\text{max}}$ . In such events, peripheral limitations involving depletion of fuel stores are not expected, at least when pre-exercise strategies have been undertaken to normalize muscle glycogen stores. Several studies have shown that an increase in muscle glycogen stores via CHO loading protocols does not lead to improved performance in field studies or laboratory protocols of this duration (13, 26). On this basis, supplying additional CHO immediately before or during an event lasting 60 min would not be expected to improve performance, at least by any mechanism that involved glycogen sparing or provision of an additional fuel substrate in the face of glycogen depletion.

Since blood glucose concentrations are usually maintained or even slightly elevated by exercise around these intensities, as seen in our study, it is unlikely that CHO intake provides an advantage in terms of preventing or reversing frank hypoglycemia. Instead, several authors have suggested that there might be more subtle alterations in sensory input following CHO consumption during high-intensity work. Carter and co-workers (6) proposed two theories: first, slightly higher blood glucose concentrations influence the sites affecting motivation, pacing, and motor output in the central nervous system or higher brain center; or alternatively, CHO intake communicates directly to these brain centers via stimulation of receptors and nerve endings in the mouth and gastrointestinal tract. Follow-up studies from this group cast doubt on the first theory when elevation of blood glucose concentrations via intravenous glucose delivery failed to alter performance of a 1 h cycling time trial (8). Support for the second theory was found, however, when the use of

**Table 4 Studies of Carbohydrate (CHO) Intake Immediately Before and/or During High-Intensity Exercise ~ 1 H Duration**

Study	Subjects	Supplement protocol	Exercise protocol	Enhanced endurance/performance	Comments
Hot environment Below et al. 1995 (4)	Well-trained cyclists (8 M) Crossover design with CHO +/- fluid replacement	~1.1 g/kg CHO Treatments: 1330 mL of 6% CHO or 200 mL of 40% CHO drink vs. fluid only Intake: Ad libitum intake during trial	Cycling 50 min @ 80% VO <sub>2max</sub> + ~10 min TT	Yes	Overall, CHO was associated with 6.3% enhancement of TT performance compared with no CHO replacement, $P < 0.05$ . No differences in physiological parameters between CHO and no CHO trials.
Carter et al. 2003 (6)	Trained cyclists (8 M) Crossover design	~ 1 g/kg CHO Treatments: 6% CHO drink vs. placebo. Intake: 8 mL/kg immediately before trial + 3 mL/kg every 15 min	Cycling 73% VO <sub>2max</sub> to exhaustion	Yes	Time to exhaustion was increased by 13.5% with CHO (60.6 ± 11.1 min) compared with flavored placebo (50.8 ± 7.5 min), $P < 0.05$ . No differ- ence between rate of rectal tem- perature rise, although trend to higher temp at exhaustion with CHO. Blood glucose maintained in both trials, but slightly higher with CHO.
Millard-Stafford et al. 1997 (21)	Well-trained runners (10 M) Crossover design with 2 different types of CHO drink	~0.7-1.0 g/kg; Treatments: 6 or 8% CHO drinks vs. placebo Intake: 1 L before run, ad libitum during run	Running 15 km treadmill run; 13.4 km at steady state then 1.6 km TT	Yes	Both CHO drinks enhanced TT performance (6% CHO: 344 s for 1.6 km TT; 8% CHO 341 s) compared to flavored placebo (358 s), $P < 0.05$

Cool/moderate environment or environment not stated	<p>Neufer et al. 1987 (22)</p> <p>Well-trained cyclists (10 M)</p> <p>Crossover design with solid and liquid CHO</p>	<p>~0.6 g CHO</p> <p>Treatments: solid CHO, CHO drink vs. placebo</p> <p>Intake: immediately before exercise</p>	<p>Cycling</p> <p>45 min @ 77% <math>VO_{2max}</math> then TT</p>	<p>Yes</p> <p>Greater work done with solid and liquid forms of CHO (~175 kNm) compared with placebo (159 kNm), <math>P &lt; 0.05</math>. No glycogen sparing with CHO intake.</p>
Anantaramen et al. 1995 (3)	<p>Trained subjects (5 M)</p> <p>Crossover design with pre-CHO and pre+ during CHO</p>	<p>~0.5 or 2 g/kg CHO</p> <p>Treatments: 10% CHO drink vs. placebo</p> <p>Intake: 300 mL immediately before, or 300 mL before and 300 mL every 15 min</p>	<p>Cycling</p> <p>60 min protocol starting at 90% <math>VO_{2max}</math> and declining as necessary</p>	<p>Yes</p> <p>Workload maintained in all trials until 40-60 min where greater drop off in power with placebo trial. Total work done during trial was higher in both pre-CHO trial (619 ± 234 kJ, and pre+during CHO trial (599 ± 235 kJ) compared with placebo (560 ± 198 kJ), <math>P &lt; 0.05</math></p>
Jeukendrup et al. 1997 (18)	<p>Well-trained cyclists (19 M+F)</p> <p>Crossover design</p>	<p>1.1 g/kg CHO</p> <p>Treatments: 8% CHO drink vs. placebo</p> <p>Intake: 14 mL/kg consumed in equal portions immediately before and each 25% of TT</p>	<p>Cycling</p> <p>TT to complete work expected to last about ~1 h</p>	<p>Yes</p> <p>TT performance with CHO (58.74 ± 0.52 min; mean power = 297W) was enhanced compared with performance with a flavored placebo (60.15 ± 0.65 min, mean power = 291 W), <math>P &lt; 0.001</math></p>

(continued)

Table 4 (continued)

Study	Subjects	Supplement protocol	Exercise protocol	Enhanced endurance/performance	Comments
Kovacs et al. 1998 (19)	Well-trained cyclists (15 M) Crossover design	~ 1 g/kg CHO Treatments: 7% CHO drink vs. placebo Intake: 14 mL/kg consumed as 8 mL/kg immediately before and 3 mL/kg at ~ 20 and 40 min of TT.	Cycling TT lasting ~ 1h	No	Similar times to complete TT in CHO trial ( $62.5 \pm 1.3$ min) and placebo ( $61.5 \pm 1.1$ min), NS.
Nikopoulos et al. 2004 (24)	Well-trained cyclists (8 M) Crossover design	~ 1 g/kg CHO Treatments: 6.4% CHO drink vs. placebo Intake: 14 mL/kg consumed as 8 mL/kg immediately before and 2 mL/kg at 15 min intervals.	Cycling Time to fatigue @ 85% $\dot{V}O_{2max}$	Probably	Strong trend for increase in endurance: 13% increase in time to exhaustion with CHO (58:54 $\pm$ 8:48 min) compared with flavored placebo (51:18 $\pm$ 5:54 min), NS. Surface EMG same for first 30 min in each trial; after 45 min and at fatigue, EMG lower in CHO trial. Suggests neural mechanism for CHO effect.

Desbrow et al. 2004 (11)	Well-trained cyclists/ triathletes (9 M) Crossover design	0.8 g/kg Treatments: 6% CHO drink vs. placebo Intake: 14 mL/kg consumed as 8 mL/kg immediately before and 2 mL/kg at ~ 25, 50, 75% of TT.	Cycling TT lasting ~ 1h	No	No difference in TT performance between CHO (62:34 ± 6:44 min) and placebo trials (62:40 ± 5:35 min). No differences in post-TT blood glucose concentrations between trials.
Van Nieuwenhoven et al. 2005 (27)	Trained to well-trained runners (90 M + 8 F) Crossover design	~ 0.6 g/kg Treatments: 7% CHO drink vs. water Intake: 600 mL consumed in equal portions before and at 4.5, 9, and 13.5 km of race	Running 18 km road race	No	No differences in performance of whole group between water (78:03 ± 8:30 min) and carbohy- drate trials (78:23 ± 8:47 min), or for 10 fastest runners (63:50 vs. 63:54 min for water and carbohy- drate, respectively).
Burke et al. (present study)	Highly-trained distance runners (18M) Crossover design	1.1 g/kg Treatments: CHO gel vs. placebo Intake: dose split between immediately before, and at 7 km and 14 km	Running Half-marathon (field study)	No	Differences in half-marathon time trivial: 73:56 vs. 73:35 min for placebo and CHO (difference = 0.3%, NS).

*Note.* M, male; F, female; TT, time trial; CHO, carbohydrate;  $VO_{2max}$ , maximal  $O_2$  uptake

a CHO-containing mouthwash during a similar protocol increased power output and achieved a 3% faster performance time compared with a placebo mouthwash (7). Presumably triggering of CHO receptors in the oral cavity led to stimulation of areas in the brain associated with motivation or pacing, allowing cyclists to complete the time trial at a higher work output but with a similar sense of pacing and perceived effort. Finally, a study from Nikolopoulos et al. found that CHO intake was associated with a reduction in surface EMG activity in the muscles with the increased duration of high-intensity cycling and at the point of fatigue (24). These investigators suggested that CHO intake changes afferent sensory input, and that a neural control mechanism (a “governor”) could be responsible for reducing or limiting exercise capacity. Further studies are needed to explore these theories.

Differences in the exercise protocols employed in existing studies are an obvious consideration when reconciling the results of our investigation against the background literature. Such differences include the mode of exercise, as well as the choice of a defined endpoint (e.g., time trial) or an open ended (e.g., time to exhaustion) design. In terms of the measurement of exercise outcomes, CHO intake during exercise lasting ~ 1 h improves the outcomes of both time to exhaustion (6, 24) and performance (4, 18, 21, 22) tasks. On the other hand, studies including the present investigation that have failed to detect a performance outcome have all involved a time-trial or fixed outcome (11, 19, 27). Other researchers have noted that the magnitudes of effects due to other nutrition interventions vary according to the exercise protocol: benefits of bicarbonate (20) and caffeine (12) are more pronounced in time to exhaustion protocols than performance tests. This outcome might be related to the reliability of protocols as well as the type and magnitude of the effect of the treatment (12). While this observation could help to explain an increased likelihood to fail to detect a performance benefit following CHO ingestion in a time trial, it does not explain the absence of a worthwhile effect. Differences in the mode of exercise are another possibility, since substrate utilization when CHO is consumed is known to vary substantially between running and cycling at the same relative intensity (10). As noted earlier, however, the metabolic fate of ingested CHO does not appear to be an important factor in performance changes during high-intensity exercise lasting ~ 1 h; furthermore, one of two available studies of CHO intake during high-intensity running reported a beneficial outcome (21). Therefore, neither the mode nor the type of exercise protocol provides a satisfactory explanation for differences in the literature regarding CHO intake during 1 h exercise.

Another possible explanation for variations in studies examining CHO intake and exercise performance is thermoregulation in adverse environmental conditions. The key studies addressing the issue of CHO ingestion and exercise performance have involved different environmental conditions, with all three of the studies targeting exercise in the heat (4, 6, 21) reporting that CHO intake provided benefits to high-intensity exercise performance. In the study by Carter and colleagues (6), subjects in the CHO trial were able to cycle for ~ 10 min longer and had a slightly higher rectal temperature at the point of fatigue than in the control trial. According to the theory of critical core temperature, a high body temperature results in an inhibition of motor activity, perhaps involving the hypothalamus, to reduce heat production and protect the body against a further temperature rise (23). Therefore,

the authors speculated that CHO intake could have had the effect of allowing subjects to tolerate a higher core temperature. Although this might provide one explanation and support for an augmented effect of CHO intake during high-intensity exercise in the heat, hot conditions are not a prerequisite for beneficial outcomes of CHO supplementation, since several studies conducted in moderate temperatures have also reported these findings (3, 18, 22, 24). Therefore, mild environmental conditions cannot explain the lack of a detectable performance enhancement with CHO intake experienced during this investigation.

A final consideration is the pre-race CHO status of subjects prior to time trial performance. Although the studies in the existing literature typically imposed a training and dietary preparation over the day(s) leading up to trials to normalize muscle glycogen stores, there were differences in the feeding protocols in the hours before exercise. Studies in which subjects undertook an overnight fast prior to exercise (4, 6, 22) showed that CHO intake immediately during and/or immediately before exercise enhanced endurance performance. In the present study and that of Desbrow et al. (11), subjects received a pre-race meal supplying 1 to 2 g CHO/kg BM, as directed by sports nutrition guidelines (2) and typical of the normal practice of most endurance athletes. Although this is a common feature of two studies in which CHO supplementation failed to enhance exercise performance, it is difficult to see how pre-race nutritional practices might interact with the central nervous system stimulation from CHO intake consumed during ~1 h time trial performance.

Many aspects of the current investigation, particularly the field study design and the incorporation of real-life strategies of distance runners, targeted the practical aspects of sports nutrition guidelines. Other investigators have identified that time lost in handling race eating and drink strategies must be considered in the decision to consume fluid and CHO during endurance events (9), and that the intake of concentrated beverages poses a risk factor for the development of gastrointestinal problems during exercise (5). The runners in our study appeared to be slowed down by the intake of the gels during the race. The lost time, however, amounted to a couple of seconds over the race, which was easily covered by the trivial enhancement of race time during the CHO trial. A small number of runners reported some degree of gastrointestinal discomfort during the race in which they consumed the sports gels, and this was associated with a clear impairment of running performance. It is likely that further practice with the use of gels during training sessions and races would reduce or eliminate both of these practical problems. Indeed, we noted that almost all of the runners stated that they would use sports gels again in a half-marathon or marathon event. This is an interesting finding in view of the conservative practices of our subjects and distance runners in general, and because our runners were able to distinguish the race in which they performed best; some were therefore aware that they had produced a faster race time on the placebo trial.

In summary, we failed to find evidence of a worthwhile enhancement of half-marathon running performance following the intake of CHO via consumption of commercial sports gels. The positive findings in the general literature and the interest shown by highly trained athletes, however, suggests that further investigation of the effects of CHO intake during sporting events involving high-intensity exercise lasting about 1 h is warranted.

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