Strategies of Dietary Carbohydrate Manipulation and Their Effects on Performance in Cycling Time Trials

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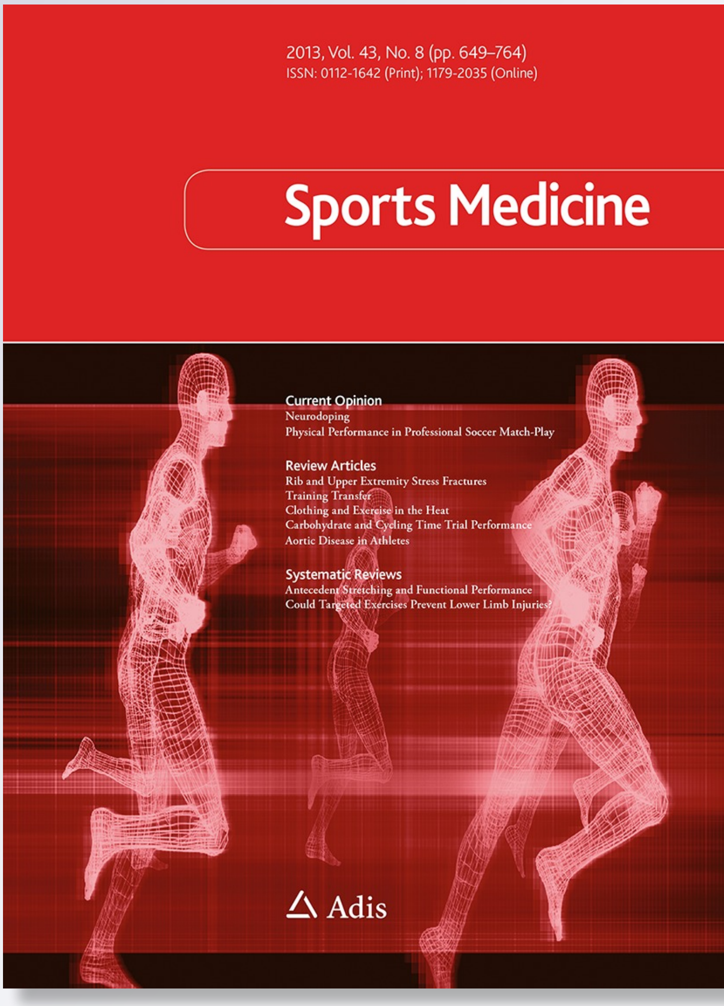

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REVIEW ARTICLE

Strategies of Dietary Carbohydrate Manipulation and Their Effects on Performance in Cycling Time Trials

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Abstract The relationship between carbohydrate (CHO) availability and exercise performance has been thoroughly discussed. CHO improves performance in both prolonged, low-intensity and short, high-intensity exercises. Most studies have focused on the effects of CHO supplementation on the performance of constant-load, time-to-exhaustion exercises. Nevertheless, in the last 20 years, there has been a consistent increase in research on the effects of different forms of CHO supplementation (e.g. diet manipulation, CHO supplementation before or during exercise) on performance during closed-loop exercises, such as cycling time trials (TTs). A TT is a highly reproducible exercise and reflects a more realistic scenario of competition compared with the time-to-exhaustion test. CHO manipulation has been performed in various time periods, such as days before, minutes before, during a TT or in a matched manner (e.g. before and during a TT). The purpose of this review is to address the possible effects of these different forms of CHO manipulation on the performance during a cycling TT. Previous data suggest that when a high-CHO diet (~70 % of CHO) is consumed before a TT (24–72 h before), the mean power output increases and reduces the TT time. When participants are supplemented with CHO (from 45 to 400 g) prior to a TT (from 2 min to 6 h before the TT), mean power output and time seem to improve due to an increase in CHO oxidation. Similarly, this performance also seems to increase when participants ingest CHO during a TT because such consumption maintains plasma glucose levels. A CHO mouth rinse also improves performance by activating several brain areas related to reward and motor control through CHO receptors in the oral cavity. However, some studies reported controversial results concerning the benefits of CHO on TT performance. Methodological issues such as time of supplementation, quantity, concentration and type of CHO ingested, as well as the TT duration and intensity, should be considered in future studies because small variations in any of these factors may have beneficial or adverse effects on TT performance.

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1 Introduction

Several studies have reported the importance of dietetic carbohydrate (CHO) as an energy source for exercise [1–3]. An increase in CHO availability promotes a performance improvement during prolonged, low-intensity [1, 3, 4] and short, high-intensity exercises [2, 5–7]. In general, CHO manipulation has usually been performed days before exercise (from 24 to 72 h) [4, 8], minutes to hours before exercise (from 2 min to 6 h) [9–12], during exercise (e.g. at intervals of 15 or 20 min during exercise) [13–15] or in a matched manner (e.g. before and during exercise) [16–19]. Additionally, some recent studies have utilized a CHO mouth rinse as an ergogenic resource [20–23].

It has been well documented that when athletes are fed with CHO, there is an increase in their time to exhaustion during constant-load exercises (i.e. performance) [3, 5, 7, 24, 25]. However, in time-to-exhaustion exercises in which the athletes are required to maintain a fixed intensity, some factors, such as lack of motivation and boredom, may be pronounced. Therefore, in the last 20 years, several studies have focused on the effects of CHO loading on performance in more motivational exercises that simulate more realistic scenarios of competition, such as time trials (TTs), in which the athletes are free to vary their exercise intensity [26–29]. In fact, a TT is less variable compared with a time-to-exhaustion test [30]. This finding suggests that TTs are highly reproducible and reflect a realistic scenario of competition [30–32]. Therefore, it would be helpful for athletes and coaches to determine which strategies of CHO manipulation are beneficial to TT performance.

The purpose of the present review is to address the possible effects of different strategies of CHO manipulation on cycling TT performance. The strategies of CHO manipulation were operationally classified as (1) CHO diet manipulation before a TT, including a CHO load starting at least 24 h prior to a TT; (2) CHO supplementation before a TT, defined as CHO supplemented between 2 min and 6 h before a TT; (3) CHO supplementation during a TT (i.e. regularly provided during the TT); and (4) CHO mouth rinse during a TT (i.e. non-ingested CHO mouth rinse provided at the beginning of and during the TT). Studies that combined CHO diet manipulation before and during a TT were also considered [4, 8, 33]. A search was conducted in the PubMed and MEDLINE databases (no lower date limit; articles published up to 31 July 2012). Initially, we used the following keywords: 'carbohydrate diet', 'dietary carbohydrate manipulation', 'carbohydrate supplementation', 'carbohydrate intake', 'carbohydrate mouth rinse', 'carbohydrate loading', 'exercise performance', 'time trial performance' and 'cycling time trial performance'. The search yielded 92 potentially eligible studies. The reference lists of all of the identified articles were fully and carefully checked. We intended to identify articles that met the following criteria: (a) articles that showed a link between CHO supplementation, diet or mouth rinse and TT performance; (b) studies involving humans; and (c) studies pertaining to cycling. A total of 30 studies that compared (a) the effects of a high-CHO diet with a control and/or low-CHO diet; and (b) the effects of CHO supplementation or mouth rinse with no CHO supplementation, i.e. placebo (PLA), were identified and included in the review. The selected studies were published between March 1987 and April 2012. Additionally, because some studies were funded or supported by sports drink or food companies, we also investigated whether there was any publication bias.

2 Carbohydrate (CHO) and Cycling Time-Trial (TT) Performance

2.1 CHO Diet Manipulation Before a TT

A few studies have investigated the influence of CHO dietary manipulation on performance during a cycling TT and have produced conflicting results (Table 1) [4, 8, 33–36]. A potential confounding factor is that studies investigating the effects of high-CHO diets on performance have used control diets with already elevated CHO contents. In addition, a diet prescription based on grams per body mass (g/kg/BM) instead of a percentage of CHO relative to the total energy expenditure may produce a bias that leads to variable CHO contents in the diets of athletes with different energy expenditures.

The first study using a TT was conducted by Hawley and colleagues [34], who investigated whether elevating the pre-exercise muscle glycogen content would result in a better performance during a 1-h cycling TT. Six well-trained endurance cyclists were submitted to 3 days of either a high-CHO diet (mean ± standard deviation [SD] 9.3 ± 0.7 g/kg/BM) or a control diet (5.9 ± 1.4 g/kg/BM). Although the pre-exercise muscle glycogen content was elevated by the high-CHO diet (mean ± SD, 565 ± 62 vs. 459 ± 83 mmol/kg dry weight; $p < 0.05$), the distance covered was similar during both conditions (mean ± SD, high-CHO: 40.18 ± 1.76 km; control: 40.41 ± 1.44 km). Furthermore, the average power output was similar between the diets (mean ± SD, 264 ± 29 vs. 262 ± 29 W). The authors suggested that the diet manipulation did not provide any performance benefits because the athletes regularly consumed diets with moderate- to high-CHO content, suggesting that the athletes were CHO adapted. However, it should also be noted that the control diet had a considerable amount of CHO, which, per se, would be a high-CHO diet and could mask any performance effect of additional CHO.

To the best of our knowledge, no other study has investigated the isolated effect of a CHO diet manipulation prior to a TT. Several other studies have used a combined CHO manipulation approach (before and during exercise). For example, Burke et al. [33]. investigated the effect of a 3-day, high-CHO diet before a 100-km TT followed by glucose supplementation during the exercise. Seven endurance-trained cyclists underwent the test after either a high-CHO diet (9 g/kg/BM/day) or a placebo-controlled diet (6 g/kg/BM/day). In both conditions, a glucose solution (7 g/100 mL) was provided at a rate of 15 mL/kg/BM/h during the TT. Although the muscle glycogen level increased after the high-CHO diet (mean ± SD, 572 ± 107 vs. 485 ± 218 mmol/kg dry weight), the mean time and power output during the TT did not differ between the two

Table 1 Effects of a prior carbohydrate diet on performance in a cycling time trial

Study	Sample size (n)	Participants	$\dot{V}O_{2max}$ (L/min) [mean ± SD]	$\dot{V}O_{2max}$ (mL/kg) [mean ± SD]	Exercise protocol	Supplementation protocol	When consumed	Performance	Financial support
Bishop et al. [35]	12	T	NR	61.7 ± 2.5	1 h at 60 % W_{max} followed by a ~30-min TT (amount of work equivalent to 30 min at 80 % W_{max})	High-CHO diet (8.4 g/kg) or low-CHO diet (1.1 g/kg)	3 days before the TT	Improved (~26.6 %)	No
Bishop et al. [36]	7	T	NR	63.4 ± 3.4	1 h at 60 % W_{max} followed by a ~30-min TT (amount of work equivalent to 30 min at 80 % W_{max})	High-CHO diet (8.8 g/kg) or low-CHO diet (1.1 g/kg)	3 days before the TT	Improved (~33.4 %)	No
Burke et al. [33]	7	T	4.6 ± 0.6	NR	100-km TT	High-CHO diet (9 g/kg) or placebo-controlled diet (6 g/kg). CHO offered also at 1 g/kg during the TT	3 days before and during the TT	Not improved	Yes
Hawley et al. [34]	6	WT	4.5 ± 0.3	NR	1-h TT	High-CHO diet (9.3 g/kg) or control-CHO diet (5.9 g/kg)	3 days before the TT	Not improved	No
Johnson et al. [4]	8	T	NR	72.5 ± 2.2	3-h TT	High-CHO diet (9 g/kg) or low-CHO diet (0.1 g/kg). CHO (7 % glucose) offered during the TT	2 days before the TT and during exercise	Improved (NR)	No
Rauch et al. [8]	8	T	4.7 ± 0.1	NR	120 min at 65 % W_{max} followed by a 1-h TT	High-CHO diet or control-CHO diet. CHO (10 % glucose) offered during the TT	3 days before the TT and during the first 2 h of CLE	Improved (~ 6 %)	No

CHO carbohydrate, *CLE* constant-load exercise, *NR* not reported, *SD* standard deviation, *T* trained, *TT* time trial, $\dot{V}O_{2max}$ maximal oxygen uptake, W_{max} maximum power output, *WT* well-trained conditions (mean ± SD, 147.5 ± 10 min and 258.7 ± 40.1 W vs. 149.1 ± 11 min and 253 ± 40.1 W). One possible explanation for this result is that participants were not aware of their altered CHO status. The authors suggested that the subjects' knowledge that they were CHO loading could be an important determinant of the measured ergogenic effect of CHO-loading studies that are not placebo controlled. It could also be argued that the high-CHO diet may not have had a beneficial effect on performance because muscle glycogen content was also elevated by the control diet. The glucose maintenance caused by glucose supplementation during the trials also could have improved the performance during the control test. In fact, the use of glucose supplementation during a race confounds the unique effect of previous diet manipulation on performance [37, 38].

In a reanalysis of their previously published study [39], Rauch et al. [8] showed that the muscle glycogen content of well-trained endurance cyclists increased approximately 45 % (mean ± standard error of the mean [SEM], from 104 ± 11 to 151 ± 9 mmol/kg dry weight) after 3 days of a high-CHO diet (mean ± SEM, 10.5 ± 0.5 g/kg/BM/day). Cyclists taking control-CHO diet consumed ~6 g/kg/BM/day (mean = 6.1 ± SEM = 0.2 g/kg/BM/day). The performance was measured during a 1-h TT, which was performed immediately after a 2-h constant-load exercise (65 % of the maximum power output). The performance was optimized (approximately 14 %) after the high-CHO diet, but the muscle glycogen content at the end of the trials was similar between the conditions (mean ± SEM, 20 ± 3 vs. 18 ± 3 mmol/kg dry weight), indicating that the participants were able to utilize the additional muscle glycogen in the high-CHO condition. It should be noted that the CHO content in this high-CHO diet was greater than in Hawley's and Burke's studies [33, 34], while the CHO content in the control-CHO diet was similar to those studies, suggesting that differences in performance may have been due to the athletes' consumption of a much larger CHO amount in the high-CHO diet condition.

In a pair of studies, Bishop et al. [35, 36] demonstrated that performance on a 30-min cycling TT was enhanced when trained cyclists consumed a high-CHO diet (~8.5 g/kg/BM/day) compared with a low-CHO diet (1.1 g/kg/BM/day). The diets were started immediately after a glycogen-lowering bout and were performed for 3 days. Johnson and colleagues [4] also confirmed these findings using a placebo-controlled design (artificially sweetened water), in which eight endurance-trained cyclists performed an exercise protocol to deplete muscle glycogen, followed by consumption of ten bottles (five per day) of solution containing 9 g/kg/BM/day or 0.1 g/kg/BM/day of CHO over the course of 2 days. Then, the participants performed a 3-h TT while ingesting a 7 % glucose solution at a rate of 15 mL/kg/BM/h. This study revealed that the power output in the last 20 % of the trial was significantly lower for the low-CHO diet than for the high-CHO diet ($p < 0.05$). This decline in power output was accompanied by a similar decline in plasma glucose concentration. Notably, the differences in the CHO content between the diet conditions (high-CHO diet vs. low- or control-CHO diet) in this study (~94 %) and in Rauch's and Bishop's studies (~42 and ~87 %, respectively) [8, 35, 36] were larger compared with the those of Hawley et al. [34] and Burke et al. [33] (~36 and ~33 %, respectively). This discrepancy reinforces the notion that large differences between experimental diets may maximize differences in performance. Another important consideration is whether the participants are adapted to a high-CHO diet. Although this was not reported in the above studies, it could be argued that CHO-adapted subjects may have been more dependent on a continual supply of ingested glucose than non-CHO-adapted subjects [40]. Additional CHO supplementation during the TTs also could have confounded the results because CHO supplementation per se can influence cycling performance [14, 15]. Therefore, further research should investigate the isolated effect of diet manipulation on TT performance and report the habitual diets of the participants.

2.2 CHO Supplementation Before a TT

The effects of CHO supplementation before a TT on performance have also been investigated [9–12, 27, 41–44]. However, similar to the studies of CHO diet manipulation before a TT, these investigations have generated conflicting results (Table 2).

Some studies showed that performance during a TT is improved due to prior CHO supplementation. Sherman et al. [10, 11] conducted two studies to determine the effects of consuming different amounts of CHO before a TT. In the first study [10], ten physically active students ingested ~312 g (4.5 g/kg/BM) of CHO (high-CHO supplementation) or PLA (non-nutritive solution) 4 h before a 95-min intermittent exercise. Fifteen minutes after the intermittent exercise had finished, the students completed an amount of work equivalent to 45 min at 70 % of maximal oxygen uptake ($\dot{V}O_{2max}$). The performance during the TT was 15 % higher in the high-CHO than in the PLA condition (mean ± SEM, 47.9 ± 3.7 vs. 56.2 ± 3.5 min). In a subsequent study, Sherman et al. [11] recruited nine active students for three experimental conditions: (1) normal-CHO supplementation (2.2 g/kg/BM of CHO); (2) low CHO supplementation (1.1 g/kg/BM of CHO) and; (3) PLA (non-nutritive solution). The participants consumed the solutions 1 h before an exercise performed at 70 %

Table 2 Effects of carbohydrate supplementation before cycling time trial on performance

Study	Sample size (n)	Participants	$\dot{V}O_{2max}$ (L/min) [mean ± SD]	$\dot{V}O_{2max}$ (mL/kg/min) [mean ± SD]	Exercise protocol [mean ± SD]	Supplementation protocol	When consumed	Performance	Financial support
Anantaraman et al. [43]	5	PA	NR	51.3 ± 4.5	1-h TT	CHO supplementation (10 % glucose) or PLA	2 min before TT	Improved (~9.5 %)	No
el-Sayed et al. [12]	8	T	NR	66.5 ± 2.5	1-h TT	CHO supplementation (8 % glucose) or PLA (glucose-free solution)	Before the 20-min warm-up	Improved (~3 %)	No
Hendelman et al. [42]	13	UT	NR	52.3 ± 6.8	75 min at 60 % $\dot{V}O_{2max}$ followed by 2.5-km TT	CHO supplementation (CHO1: 36 g; CHO2: 44 g or PLA)	95 min before TT	Not improved	No
Jentjens et al. [41]	9	T	NR	64.1 ± 2.1	20 min at 65 % W_{max} followed by ~40-min TT (691 ± 12 kJ)	Low-CHO supplementation (25 g), moderate-CHO supplementation (75 g), high-CHO supplementation (200 g) or PLA (0 g)	65 min before the TT	Not improved	No
Neufer et al. [9]	10	WT	4.3 ± 0.1	NR	45 min at 80 % $\dot{V}O_{2max}$ followed by 15-min TT	SCHO (45 g), or LiCHO (45 g), or MP + SCHO (200 g) or PLA	SCHO, LiCHO and PLA (50 min before the TT). MP (~5 h before the TT) + SCHO (50 min before the TT)	Improved (~9–18 %)	No
Palmer et al. [27]	14	T	4.5 ± 0.6	NR	20-km TT (~25–30 min)	CHO supplementation (40 g CHO) or PLA	15 min before the TT	Not improved	Yes
Paul et al. [44]	8	T	NR	64.1 ± 7.9	30 min above lactate threshold followed by 20-km TT	CHO supplementation (3 g/kg CHO) or PLA	4 h before TT	Not improved	Yes
Sherman et al. [10]	10	PA	4.0 ± 0.2	NR	95 min at 52–70 % $\dot{V}O_{2max}$ followed by ~45-min TT (amount of work equivalent to 45 min at 70 % $\dot{V}O_{2max}$)	High-CHO supplementation (312 g) or PLA	6 h before the TT	Improved (~15 %)	Yes
Sherman et al. [11]	9	PA	4.1 ± 0.2	NR	90 min at 70 % $\dot{V}O_{2max}$ followed by ~45-min TT (amount of work equivalent to 45 min at 70 % $\dot{V}O_{2max}$)	Normal-CHO supplementation (2.2 g/kg), low-CHO supplementation (1.1 g/kg) or PLA	2 h and 30 min before the TT	Improved (~13 %)	No

CHO carbohydrate, *LiCHO* liquid carbohydrate, *MP + SCHO* meal prior + solid carbohydrate, *NR* not reported, *PA* physically active, *PLA* placebo, *SCHO* solid carbohydrate, *T* trained, *TT* time trial, *UT* untrained, $\dot{V}O_{2max}$ maximal oxygen uptake, W_{max} maximum power uptake, *WT* well trained

$\dot{V}O_{2max}$ for 90 min, followed by a 45-min TT (equivalent to 45 min at 70 % $\dot{V}O_{2max}$). The participants supplemented with CHO (normal- and low-CHO supplementation) had a significant improvement in both mean power output (+13.1 %) and the time of the test (−12.5 %) compared with PLA ($p < 0.05$). Although the reasons are not clear, the increases in the performance observed in both of these studies were very large and may not represent real competitions. In both studies, the results were mainly attributed to an increase in CHO oxidation. However, this interpretation is unlikely to be valid in the case of high-intensity exercises, such as a 45-min TT, as only 5–20 g of exogenous CHO are oxidized in the first hour of exercise [26]. This relatively small contribution to the total CHO oxidation rate was thought to be too small to significantly improve exercise performance. Instead, a growing body of evidence suggests that oral CHO exerts direct effects on the central nervous system [20, 22, 23], improving motor drive or motivation and therefore improving performance.

The results of Sherman et al. [10, 11] are similar to the findings of Neufer et al. [9] in well-trained cyclists. In their study, CHO (45–200 g) was ingested 5 min before a 45-min constant-load exercise at 80 % $\dot{V}O_{2max}$, followed by a 15-min TT. An additional trial was performed in which a high-CHO meal (200 g) taken 4 h before exercise was combined with a confectionery bar feeding immediately before the constant-load exercise. The average total work performed during the TT was significantly increased (+13.5 %) with CHO supplementation compared with the PLA condition. The authors associated this improvement with an increase in CHO oxidation. However, as suggested above, this outcome may be attributed to maintenance of an adequate central neural drive to the muscle.

Similarly, el-Sayed et al. [12], using a longer TT (1 h), investigated the performance-related responses of eight highly trained competitive cyclists after CHO supplementation. The cyclists ingested 4.5 mL/kg of a drink containing either an 8 % glucose solution (CHO supplementation) or PLA (glucose free) immediately before the warm-up. Performance was improved by CHO supplementation, compared with the PLA condition (mean ± SEM, 277 ± 3 W and 41.5 ± 1.06 km vs. 269 ± 3 W and 41.0 ± 1.06 km; $p < 0.05$). On the other hand, Palmer and colleagues [27] evaluated the effects of CHO intake (8 mL/kg/BM) 15 min before a 20-km TT in 14 endurance-trained cyclists. The performance was exactly the same between PLA and CHO supplementation (mean ± SD, 27:41 ± 1:39 vs. 27:41 ± 1:39 min; $p < 0.05$). Hendelman et al. [42] reported that performance during a 2.5-km TT was not improved when untrained subjects were supplemented with CHO (36–44 g). The supplement was consumed before a 75-min constant-load exercise at 60 % $\dot{V}O_{2max}$ followed by the TT. Additionally, Jentjens et al. [41] investigated, in nine endurance-trained cyclists, the effects of different amounts of glucose (25, 75 and 200 g of CHO) ingested 45 min before a 20-min constant-load exercise (65 % of the maximum power output) followed immediately by a TT (mean ± SEM, 691 ± 12 kJ). The plasma glucose concentrations during the constant-load exercise declined in all three glucose-supplemented conditions. However, the glucose concentration increased progressively in all conditions during the TT. There was no difference in the blood glucose concentration between the conditions throughout the TT. Furthermore, the mean completion time for the TT was not different between any of the conditions ($p > 0.05$).

One possible explanation for the contradictory effects of CHO supplementation on performance is the variation in the level of physical fitness. Additionally, the intensity and duration of a constant-load exercise preceding a TT and the time, amount and type of CHO ingested, as well as the interrelationship between these variables, may cause a, so-called, rebound hypoglycaemia. Rebound hypoglycaemia is characterized by a rapid fall in plasma glucose after the onset of exercise due to hyperglycaemia and hyperinsulinaemia as a result of pre-exercise CHO ingestion [45–48]. This effect has been attributed to CHO intolerance, and athletes could benefit by either ingesting CHO during the exercise or becoming more adapted to a high-fat, low-CHO diet before a trial [40]. Therefore, further studies should consider these factors when investigating the effects of pre-exercise CHO supplementation on TT performance.

2.3 CHO Supplementation During a TT

The effects of CHO supplementation during a TT have been extensively investigated (Table 3) [13–19, 26, 28, 49, 50]. Several studies have shown that CHO provides an ergogenic effect when ingested during a TT [13–15, 18, 26, 28], although not all studies have found an increase in the performance [16, 17, 19, 49, 50].

To investigate the effects of CHO on performance, Jeukendrup et al. [26] submitted trained cyclists to an approximate 1-h cycling TT. The cyclists ingested either a 7.6 % CHO solution (CHO supplementation) or PLA during the warm-up and after each 25 % of the required amount of work had been performed. The last meal was eaten 1 h before the TT. Performance was significantly improved (~2.3 %) when participants carried out the trial with CHO (mean ± SEM, 58.7 ± 0.5 min) compared with the PLA condition (mean ± SEM, 60.1 ± 0.6 min, $p < 0.05$). Although the reason for this increase was not provided by the authors, it may be hypothesized that the CHO supplementation resulted in the maintenance of blood

Table 3 Effects of carbohydrate supplementation during cycling time trial on performance

Reference	Sample size (n)	Participants	$\dot{V}O_{2max}$ (L/min) [mean ± SD]	$\dot{V}O_{2max}$ (mL/kg/min) [mean ± SD]	Exercise protocol [mean ± SD]	Supplementation protocol	When consumed	Performance	Financial support
Acker-Hewitt et al. [19]	10	T	NR	66 ± 9	20 min at 60 % W_{max} followed by 20-km TT	CHO supplementation (8 % CHO) or PLA	Immediately prior to exercise, following the 20-min CLE, and 20 min into the TT	Not improved	No
Angus et al. [14]	8	T	4.7 ± 0.09	NR	~100-km TT (35 kJ/kg)	CHO supplementation (6 % CHO) or PLA	250 mL every 15 min during the TT	Improved (~7.2 %)	Yes
Below et al. [13]	8	T	4.4 ± 0.08	NR	50-min CLE followed by ~10-min TT (certain amount of work as quickly as possible)	CHO supplementation (79 g) or PLA	At the beginning, 15, 25 and 34 min into the TT	Improved (~6.5 %)	Yes
Clark et al. [16]	43	T	NR	NR	40-km TT	CHO supplementation (7.6 % CHO) or PLA	8 mL/kg 30 min before TT. 2 mL/kg 2 min before and after 10, 20 and 30 km of the TT	Not improved	No
Currell and Jeukendrup [18]	8	T	NR	64.7 ± 3.9	120 min at 50 % W_{max} followed by ~1-h TT (certain amount of work as quickly as possible)	CHO supplementation (glucose: 1.8 g/min; glucose + fructose: 1.8 g/min) or PLA	600 mL before and 150 mL every 15 min of the CLE. 150 mL at 25, 50 and 75 % of completion of the TT	Improved (10–19 %)	Yes
Desbrow et al. [50]	9	WT	NR	65.1 ± 5.9	~60-min TT (certain amount of work as quickly as possible)	CHO supplementation (6 % CHO and electrolytes) or PLA	During 20–30 %, 50–60 % and 70–80 % of the total amount of work	Not improved	Yes
Hulston and Jeukendrup [28]	10	T	NR	61.7 ± 7.3	120 min at 50 % W_{max} followed by ~1-h TT (847 ± 78 kJ)	CHO supplementation (6 % CHO) or PLA	600 mL at the beginning and 150 mL every 15 min of the CLE, and at 25, 50 and 75 % of completion of the TT	Improved (~10.6 %)	Yes
Jeukendrup et al. [26]	19	T		72.9 ± 1.4 (17 men) and 64.2 ± 0.3 (2 women)	~60-min TT (certain amount of work as quickly as possible)	CHO supplementation (7.6 % CHO) or PLA	8 mL/kg during warm-up and 2 mL/kg at 25, 50 and 75 % of completion of the TT	Improved (~2.3 %)	Yes
Jeukendrup et al. [17]	12	T	NR	66.4 ± 6.2	~25-min TT (457 ± 37 kJ)	CHO supplementation (6 % CHO) or PLA	4 mL/kg before and every 25 % of completion of the TT	Not improved	Yes
Madsen et al. [49]	9	WT	NR	63.1 ± 1.5	100-km TT	CHO supplementation (5 % CHO) or PLA	At the beginning, after 15 min (200 mL), after 35 min (350 mL) and after 30 min (350 mL) of the TT	Not improved	No
van Essen and Gibala [15]	10	T	NR	63.0 ± 2.0	80-km TT	CHO supplementation (6 % CHO) or PLA	250 mL every 15 min of the TT	Improved (~4 %)	Yes

CHO carbohydrate, *CLE* constant-load exercise, *NR* not reported, *PLA* placebo, *T* trained, *TT* time trial, $\dot{V}O_{2max}$ maximal oxygen uptake, W_{max} maximum power output, *WT* well-trained glucose levels and provided a higher rate of CHO oxidation. However, it seems unlikely that endogenous CHO is limiting during an exercise of this nature, as only 5–20 g of exogenous CHO are oxidized in the first hour of exercise. Instead, this improvement in the performance could be related to an improved motor drive or motivation, mediated by CHO receptors in the oral cavity [20, 22, 23].

Using a longer TT, Angus et al. [14] verified the efficacy of CHO intake on performance during an approximate 100-km TT (35 kJ/kg) in endurance-trained cyclists and triathletes. The last meal (breakfast) was consumed 2 h before the trial, similar to a meal that is normally ingested before competition. Athletes ingested either a 6 % solution containing CHO (CHO supplementation) or PLA at the beginning of the trial and at 15-min intervals during the trial (250 mL). The average TT completion time was significantly lower in the CHO supplementation condition (mean ± SEM, 166 ± 7 min) than in the PLA condition (mean ± SEM, 178 ± 11 min), while the power output at the end of the trial was significantly lower in the PLA (mean ± SEM, 212 ± 18 W) than in the CHO supplementation condition (mean ± SEM, 257 ± 7 W). The increase in performance was accompanied by an increase in CHO oxidation and the maintenance of the plasma glucose concentration. These results corroborate the findings of van Essen and Gibala [15], who also observed better performance and higher plasma glucose in ten trained cyclists (fed state) when supplemented with CHO every 15 min (6 % CHO diluted in 250 mL of water) during an 80-km TT.

Currell and Jeukendrup [18] also demonstrated that performance during a 60-min TT was improved when trained cyclists were regularly supplemented with CHO (1.8 g/min of CHO) compared with water. The supplements were ingested during a constant-load exercise (120 min at 55 % of maximum power output) that preceded the TT, as well as during the TT. Similarly, Hulston and Jeukendrup [28] provided a solution with 6 % CHO to ten endurance-trained cyclists. The athletes began the trial after a 3-h fast and consumed the solution at the beginning of (600 mL) and every 15 min during a 120-min constant-load exercise at 61 % $\dot{V}O_{2max}$ (150 mL). The constant-load test was followed by an 800-kJ TT. The CHO solution (150 mL) was also consumed at every 25 % of work completed during the TT. The authors found that CHO supplementation improved performance by approximately 10.6 % compared with the PLA solution (mean ± SD, 59.6 ± 2.8 vs. 65.9 ± 5.5 min). Because the participants believed that they had ingested CHO in the PLA condition, the authors suggested that any fatigue sensations associated with prolonged exercise could have overridden any positive psychological effects manifesting as a result of believing one has received a beneficial treatment. In addition, it could be hypothesized that if the athletes were fat-adapted, they most likely would be able to maintain their blood glucose levels during exercise and would be less likely to benefit from carbohydrate ingestion during a race.

In contrast, Madsen et al. [49] showed that the performance of nine well-trained cyclists during a 100-km TT was not improved by a 5 % CHO solution (85.7 g maltodextrin and 87.5 g glucose) supplemented during the TT (200 mL after 15 min, 350 mL after 35 min, and then 350 mL every 30 min) compared with the PLA condition (mean ± SEM, 160.1 ± 4.1 vs. 159.8 ± 3.7 min). The authors suggested that due to the elevated physical fitness of the athletes, they were able to maintain their supply of energy from fat oxidation in the PLA condition. Although this hypothesis was not addressed in the study, it could be expected that if the athletes usually consume a low-CHO diet, they will become fat-adapted, and fat oxidation will sufficiently replenish their CHO [51, 52]. Furthermore, the cyclists were evaluated 4 hours after their last meal, while in other studies [38, 53] that demonstrated an improvement in performance, the athletes were evaluated after an overnight fast. The findings of Madsen et al. [49] suggest that the beneficial effect of CHO supplementation can only be identified when the TT is performed in a non-fed state. Similar findings were reported by Desbrow et al. [50], who demonstrated that the performance (mean ± SD, CHO supplementation: 62.34 ± 6.44; PLA: 62.40 ± 5.35 min) of nine fed and well-trained cyclists and triathletes was not improved after ingesting 14 mL/kg of a 6 % solution of CHO (8 mL/kg bolus during warm-up and 2 mL/kg at 20–30 %, 50–60 %, and 70–80 % of the total amount of work). Corroborating these results, Jeukendrup et al. [17] found no effect of a CHO supplement (6 % CHO solution) on performance when trained cyclists ingested the supplement after a 3-h postprandial fast. Similarly, Acker-Hewitt et al. [19] also demonstrated that the performance of ten fed, trained cyclists during a 20-km cycling TT was not improved by CHO supplementation (mean ± SEM, CHO supplementation: 43.8 ± 4.1 min and 245 ± 42 W; PLA: 44.2 ± 4.5 min and 238 ± 42 W; $p > 0.05$). The supplement (20 g CHO, 8 % solution, 250 mL) was provided immediately prior to exercise, immediately after a 20-min constant-load exercise (~60 % of their maximum power output) and at 20-min intervals throughout the TT. The authors attributed the results to the initial nutritional status of the participants, supporting the notion that performance does not improve with CHO supplementation when the athletes commence a TT in a fed state.

Although the mechanisms responsible for increased performance with CHO intake during a TT have not been fully elucidated, this increase has been occasionally attributed to the maintenance of blood glucose levels (preventing hypoglycaemia) and a higher rate of CHO oxidation [1, 54–56]. In fact, in all analysed studies (except one that did not report the blood glucose concentration), an improvement in the performance was accompanied by a maintenance of the blood glucose concentration. While this explanation may explain the CHO effect on performance during long TTs (>60 min), it does not seem to be a reasonable explanation for short TTs. In this regard, as suggested recently, oral CHO may exert its effects during high-intensity exercise through a central action, mediated by receptors in the mouth or gastrointestinal tract [20, 22, 23]. Additionally, during both long and short TTs, several other mechanisms besides dose-dependent relationships between CHO ingestion, blood glucose and increased performance have been suggested [57]. For instance, the increase in CHO oxidation during exercise with CHO ingestion cannot fully explain how the muscle can either sustain or develop more force after CHO supplementation [57]. Instead, a multifactorial mechanism including centrally mediated effects, attenuation of the changes in metabolite levels in the muscle fibres, and maintenance of the electrical properties of the membrane by the improved Na^+/K^+ and/or Ca^{2+} pump activities have been proposed [57]. However, no data appear to be currently available that show whether one or more of these effects occur during a TT. In addition, the maintenance of blood glucose may be associated with the level of adaptability of the participants with high-CHO diets or CHO supplements. It could be suggested that if the athletes are CHO-adapted, they will be more dependent on CHO supplementation during exercise than fat-adapted athletes. Additionally, the pre-exercise dietary condition of the participant should be considered because any 'pre-loading' of CHO may suppress or mask any positive effects of CHO supplementation on TT performance. Additional studies should be performed to investigate the isolated effect of CHO supplementation on TT performance because the CHO load prior to a TT may confound the results.

2.4 CHO Mouth Rinse During a TT

In the last decade, the effects of non-ingested CHO mouth rinses on TT performance have also been investigated [20–23]. Although few CHO mouth rinse studies have employed TTs, the results of these studies are interesting and deserve attention (Table 4).

The first of these studies was conducted by Carter et al. [20], who investigated the effect of a CHO mouth rinse solution on performance during a 1-h cycling TT. Nine endurance-trained participants performed, after a 4-h fasting period, a certain amount of work (mean ± SD, 914 ± 40 kJ). A 25-mL bolus of mouth rinse containing either 6.4 % maltodextrin (CHO mouth rinse) or water (PLA) was provided for 5 s during warm-up and at every 12.5 % of the TT. The mean performance times were significantly faster in the CHO mouth rinse condition than in the PLA condition (mean ± SEM, 59.57 ± 1.50 vs. 61.37 ± 1.56 min; $p < 0.05$). Although the mechanism responsible for performance improvement was unknown, the authors suggested that performance may have been improved by a 'non-metabolic' and centrally mediated effect.

To establish the mechanisms by which CHO mouth rinses increase performance, Chambers et al. [22] submitted endurance-trained cyclists to a series of four studies. In study 1A, eight participants performed a ~1-h cycling TT (mean ± SD, 914 ± 29 kJ) after rinsing with 25 mL of either a 6.4 % glucose solution (CHO mouth rinse) or saccharin (PLA). The solution was mouth rinsed for 10 s at the beginning and at every 12.5 % completion interval of the TT. The mean performance time was significantly faster in the CHO mouth rinse condition (mean ± SD, 60.4 ± 3.7 min) relative to the PLA condition (mean ± SD, 61.6 ± 3.8 min; $p < 0.05$). In study 1B, it was found, using functional magnetic resonance imaging (*f*MRI), that the glucose mouth rise activated reward- and pleasure-related brain areas, which were unresponsive to the PLA. Likewise, in study 2A, the cycling TT performance (mean ± SD, 837 ± 68 kJ) significantly increased when cyclists rinsed their mouths with a sweet CHO, i.e. maltodextrin (mean ± SD, CHO mouth rinse: 62.6 ± 4.7 min; PLA: 64.6 ± 4.9 min; $p < 0.05$). A similar pattern of brain activation to that of glucose was identified in response to oral maltodextrin (study 1B). The authors concluded that the CHO mouth rinse activates brain areas involved in reward and motor control, suggesting the existence of CHO receptors in the oral cavity that detect CHO in the mouth regardless of sweetness.

Similarly, Pottier et al. [23] demonstrated an enhancement (+3.7 %) in performance during a ~1-h TT (mean ± SD, 975 ± 85 kJ) in 12 endurance-trained triathletes using a CHO mouth rinse (6 % sucrose/glucose solution at a rate of 14 mL/kg/BM before and during TT) compared with a PLA rinse (mean ± SD, 61.7 ± 5.1 min and 265.0 ± 26.4 W vs. 64.1 ± 6.5 min and 256.5 ± 30.8 W; $p < 0.05$). The authors suggested that the presence of CHO in the oral cavity initiated a central and motivational effect that allowed the athletes to exert more work and improve performance.

Considering practical situations where the athletes generally ingest a high-CHO diet approximately 2 h before a race, Beelen et al. [21] investigated the impact of a CHO mouth rinse (6.4 % maltodextrin solution) on TT performance in 14 endurance-trained cyclists in a fed state. The TT was performed 2 h after a standard CHO-rich breakfast,

Table 4 Effects of carbohydrate mouth rinse during cycling time trial on performance

Study	Sample size (n)	Participants	$\dot{V}O_{2max}$ (L/min) [mean ± SD]	$\dot{V}O_{2max}$ (mL/kg/min) [mean ± SD]	Exercise protocol [mean ± SD]	Supplementation protocol	When consumed	Performance	Financial support
Beelen et al. [21]	14	T	NR	NR	~1-h TT (1,053 ± 48 kJ)	CHO mouth rinse (6.4 % maltodextrin solution) or PLA for 5 s	25 mL at the start and every 12.5 % of TT completed	Not improved	No
Carter et al. [20]	7	T	NR	63.2 ± 8.0	~1-h TT (914 ± 40 kJ)	CHO mouth rinse (6.4 % maltodextrin solution) or PLA for 5 s	25 mL every 12.5 % of TT completed	Improved (~2.9 %)	No
Chambers et al. [22]	8 (study 1A); 8 (study 2A)	T	NR	60.8 ± 4.1 (study 1A); 57.8 ± 3.2 (study 2A)	~1-h TT: 914 ± 29 kJ (study 1A) and 837 ± 68 kJ (study 2A).	Mouth rinse with 6.4 % glucose solution (study 1A), or 6.4 % maltodextrin solution (study 2A), or PLA (study 1A and 2A) for 10 s	25 mL at the start and every 12.5 % of TT completed	Improved (study 1A: ~2 %; study 2A: ~3.1 %)	No
Pottier et al. [23]	12	T	NR	61.7 ± 3.1	~1-h TT (975 ± 85 kJ)	CHO mouth rinse (6 % sucrose/glucose solution) or PLA for 5 s	14 mL/kg body weight before and every 12.5 % of TT completed	Improved (~3.7 %)	Yes

CHO carbohydrate, *NR* not reported, *PLA* placebo, *T* trained, *TT* time trial, $\dot{V}O_{2max}$ maximal oxygen uptake

and a CHO or water mouth rinse (25 mL) was performed at the beginning and at every 12.5 % of a 1-h cycling TT (1,053 ± 48 kJ). In contrast to other studies, performance was not improved by the CHO mouth rinse (mean ± SEM, 68.14 ± 1.14 min and 265 ± 5 W; PLA: 67.52 ± 1.00 min and 266 ± 5 W; $p > 0.05$). The authors suggested that the receptors in the oral cavity might only be activated when the liver or muscle glycogen stores were largely reduced, such as in a fasting situation.

Taken together, the above data suggest that activation of the CHO receptors in the oral cavity may be related to the time of the last meal or the liver and muscle glycogen stores [20–22]. Activation of these receptors activates reward and/or pleasure centres in the brain, resulting in an increase in performance.

3 Considerations About Sports Performance Research

Recently, in a series of articles in the *British Medical Journal*, several important points were brought up that should be considered to avoid compromising the applicability of results about sports drinks [58–61]. It has been proposed that an average of less than 100 participants be considered a small sample size when investigating the effects of sports drinks on performance [58, 59]. Only one of the 106 studies analysed by the *British Medical Journal* exceeded this number of participants. Because most studies used small sample sizes, it may be that their results cannot be generalized beyond people with the study group's characteristics. Although the caution exhibited by the journals' editors has increased in relation to this issue, only a few studies have included sample size calculations. In the present review, none of the studies analysed exceeded the recommended number of participants, which could be considered as a bias of these studies. Therefore, the generalization of these results should be made with caution and applied only to the population described in each study.

Another important concern is related to the funding or lack of funding of research by the sports drink and food industry. In this regard, it has been suggested that some companies have funded a number of researchers to increase the scientific credibility of their products. However, the way in which such funding has been conducted is a hotly debated issue in the scientific community because it may produce a possible conflict of interest affecting the outcomes of studies [58]. Thus, we included in our analysis whether a given study was funded by industry. Among the articles included in the present review, 13 were considered to have been funded or supported by the sports drink and food industry, while 17 were non-funded studies or did not report their funding sources. Among the funded studies, eight (61.5 %) showed a significant improvement in performance, while five (38.5 %) found no improvement. This was similar to the ratio among the non-funded studies, in which ten (58.8 %) revealed a significant improvement with CHO supplementation and seven (41.1 %) showed no improvement. Thus, although bias from the sponsorship cannot be fully disregarded, the rate of studies showing positive effects did not differ between funded and non-funded studies, at least in studies involving cycling TTs.

4 General Limitations of the Studies

It is noteworthy that in many cases, the participants may have been CHO adapted. This adaptation to CHO may have resulted from participants' habitual consumption of a high-CHO diet. On the other hand, consumption of a high-fat diet for more than 5 days increases fat oxidation [51, 52, 62] and may be accompanied by either unaffected or increased performance because the individuals can become fat adapted [40, 51, 52, 62]. An important concern about the studies is that they did not report the habitual diets of the participants, making it difficult to identify whether the athletes were CHO or fat adapted. Further studies should consider including a brief description of the habitual diets of the participants. Finally, the TTs had either a fixed time or distance. Fixed-distance TTs may be more realistic and be more transferable to the demands of athletic competition. Further studies should consider using fixed-distance TTs to investigate the effects of CHO supplementation on performance.

5 Conclusion

Dietary CHO manipulation days before (CHO load starting at least 24 h before the TT), minutes before (CHO supplemented between 2 min and 6 h before the TT), and during a TT (regularly provided during the TT) and CHO mouth rinses seem to promote improvements in performance on cycling TTs, which emphasizes the importance of CHO availability as an ergogenic resource. Improvements in TT performance after CHO manipulation seem to be associated with an increase in CHO oxidation or maintenance, an increase in blood glucose concentration and the presence of CHO receptors in the oral cavity, which activate reward and motor control areas in the brain. On the other hand, some studies failed to find improvements in TT performance with CHO manipulation. These controversial results may be due to methodological aspects, such as the time, amount and type of CHO ingested, because minimal changes in any of these factors may provide adverse or beneficial effects in terms of performance. Additionally, variations in other factors, such as the TT duration and intensity, may hinder our understanding of CHO benefits.

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