The Journal of Nutrition
Nutrient Requirements and Optimal Nutrition

Carbohydrate Ingestion during Endurance Exercise Improves Performance in Adults[1,2]

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Abstract

This study was a systematic review with meta-analysis examining the efficacy of carbohydrate (CHO) ingestion compared with placebo (PLA) on endurance exercise performance in adults. Relevant databases were searched to January 2011. Included studies were PLA-controlled, randomized, crossover designs in which CHO ingestion not exceeding 8% and between 30 and 80 g/h during exercise of ≥1 h was evaluated via time trial (TT) or exercise time to exhaustion (TTE). The between-trial standardized mean differences [effect size (ES)] and pooled estimates of the effect of CHO ingestion were calculated. Of the 41,175 studies from the initial search, 50 were included. The ES for submaximal exercise followed by TT was significant (ES = 0.53; 95% CI = 0.37–0.69; $P < 0.001$) as was the ES for TT (ES = 0.30; 95% CI = 0.07–0.53; $P = 0.011$). The weighted mean improvement in exercise performance favored CHO ingestion (7.5 and 2.0%, respectively). TTE (ES = 0.47; 95% CI = 0.32–0.62; $P < 0.001$) and submaximal exercise followed by TTE (ES = 0.44; 95% CI = 0.08–0.80; $P = 0.017$) also showed significant effects, with weighted mean improvements of 15.1 and 54.2%, respectively, with CHO ingestion. Similar trends were evident for subanalyses of studies using only male or trained participants, for exercise of 1–3 h duration, and where CHO and PLA beverages were matched for electrolyte content. The data support that ingestion of CHO between 30 and 80 g/h enhances endurance exercise performance in adults. J. Nutr. 141: 890–897, 2011.

Introduction

Many studies have investigated the role of carbohydrate (CHO)[4] ingestion during exercise. The first of these, conducted at the 1924 Boston Marathon, linked post-race blood glucose concentration with the physical condition of runners at the finish (1). In the subsequent year, runners that supplemented with confectionery during the race experienced a beneficial effect on blood glucose concentration and post-race condition (2). Methodical research on CHO ingestion during exercise subsequently emerged in the 1930s beginning with the work of Christensen and Hansen (3). However, it was not until the mid-1960s, after the first commercial CHO-electrolyte (sports) drink emerged, that a substantial body of research investigating the efficacy of CHO ingestion on exercise performance was available.

This substantial body of research has been used in the development of recommendations on CHO ingestion for promotion of optimal endurance exercise performance (4–6). These recommendations have suggested that CHO ingestion between the ranges of 30 and 80 g/h is performance enhancing for endurance exercise beyond 1 h and that a concentration of ingested CHO between 4 and 8% is not deleterious to the rate of gastric emptying. Although many studies have examined the performance effect of CHO ingestion during endurance exercise, a comprehensive systematic review and meta-analysis on the effectiveness of this dose has not been undertaken. Therefore, the aim of this study was to conduct a systematic review of randomized, placebo (PLA)-controlled trials to assess the efficacy of CHO ingestion not exceeding 8% and between 30 and 80 g/h during exercise of ≥1 h compared with PLA on endurance exercise performance in adults.

Methods

Eligibility criteria

Design. To be included, studies needed to use a crossover design where participants were randomized to receive CHO and a masked PLA during exercise. Only randomized designs were included to eliminate poorer quality studies that did not randomize participants and only crossover designs were included, because parallel designs are rare.

Interventions. Studies were included if CHO was administered in the absence of protein, fat, or potential ergogenic substance (e.g. caffeine) at a rate between 30 and 80 g/h and a concentration not >8% CHO at regular intervals throughout exercise of ≥1 h (mean + 1 SD for PLA exercise duration needed to be ≥1 h). Due to rounding associated with calculation of CHO ingestion, studies were included if the mean

[1] Author disclosures: J. Temesi, N. A. Johnson, J. Raymond, C. A. Burdon, and H. O'Connor, no conflicts of interest.
[2] Supplemental Figures 1 and 2 and Supplemental Tables 1–18 are available from the "Online Supporting Material" link in the online posting of the article and from the same link in the online table of contents at jn.nutrition.org.
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[4] Abbreviations used: CHO, carbohydrate; ES, effect size; MD, mean difference; PLA, placebo; submax+TT, submaximal exercise bout followed by time trial; submax+TTE, submaximal exercise bout followed by time to exhaustion; TT, time trial; TTE, time to exhaustion; VO_2peak, peak oxygen consumption.
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Manuscript received December 16, 2010. Initial review completed January 06, 2011. Revision accepted February 04, 2011.
First published online March 16, 2011; doi:10.3945/jn.110.137075.

ingestion rate fell between 29 and 81 g/h CHO. The control condition was required to be closely matched to the CHO treatment for taste, sweetness (via artificial sweetener), color, and/or texture and both CHO and PLA were required to be ingested at the same rates. Studies were excluded if nothing or only plain water was consumed during the control condition. We did not exclude studies on the basis of electrolyte ingestion; i.e. it was not a requirement that studies control for any electrolytes in the CHO via inclusion of electrolytes in the PLA.

Studies in which CHO ingestion preceded the onset of exercise by >20 min were excluded, because myocellular and hepatocellular glucose uptake and glycogen synthesis may have preceded exercise and thus negated acute/direct effects of glucose ingestion on performance. Studies that permitted ad libitum fluid ingestion (either treatment beverage or water) were excluded, even if identical intra-participant drinking procedures were employed. Such practice does not permit calculation of rates of fluid or CHO ingestion or concentration of consumed fluid. We did not eliminate studies on the basis of diet or exercise undertaken prior to the exercise performance trial.

Participants. Studies with able-bodied male or female participants 16 y and older were considered. Where an age range was not given, studies were accepted if the mean age minus 1 SD was ≥16 y. Studies were excluded if participants had a disability (e.g. spinal cord injury) or a condition in which performance (e.g. chronic obstructive pulmonary disease) or CHO metabolism (e.g. diabetes) were affected. Participants were categorized by fitness level as inferred by peak oxygen consumption (VO_2peak).

Outcome measures. Studies were included if performance was measured during a time trial (TT) or exercise time to exhaustion (TTE). This included: *1*) a TT measuring time to complete a predetermined distance or amount of work; *2*) a TT measuring distance completed or work done in a predetermined time; *3*) a submaximal exercise bout immediately followed by a TT; *4*) TTE measured at a predetermined exercise intensity, speed, or power output; or *5*) a submaximal exercise bout immediately followed by TTE. Studies were not excluded on the basis of type of exercise; however, studies were excluded when the submaximal exercise bout was not consistent between trials when designs *3* or *5* (above) were used. Studies employing the Loughborough Intermittent Shuttle Test or similar protocols during the submaximal or TTE components of the performance trial were excluded due to the potential for differences in exercise dose between conditions.

Studies were excluded if they placed limits on the measurement of performance, e.g. using exercise time limits when TTE was the performance measure. Studies were also excluded if they examined repeated bouts of exercise where CHO was administered after the first exercise bout to compare recovery from a previous bout of exercise.

Search strategy

Electronic database searches were performed in Allied and Complementary Medicine (via OvidSP), Cumulative Index to Nursing and Allied Health Literature (via EBSCO), Cochrane Central Register of Controlled Trials (via OvidSP), EMBASE, MEDLINE (via OvidSP), PubMed, SPORTDiscus (via EBSCO), and Web of Knowledge from earliest record to January 2011. The search strategy combined terms covering the areas of CHO ingestion and performance (**Supplemental Fig. 1** for MEDLINE Search Strategy). Both MEDLINE and PubMed were searched with limits excluding articles where the participant pool was categorized as being below the age of 18 y. The following keywords were excluded; alcohol, amenorrhea, angina, angioplasty, anorexia, arthritis, asthma, atherosclerosis, biomechanics, blood pressure, body composition, bone, cancer, cartilage, cholesterol, cirrhosis, contraceptive, cystic fibrosis, diabetes, disease, epilepsy, HIV, hypertension, injury, ischemia, menopause, obesity, osteoporosis, pregnancy, psychology, rehabilitation, smoking, steroid, stroke, surgery, and weight loss.

Selection of studies

After eliminating duplications, the search results were screened by 1 reviewer (J.T.) against the eligibility criteria and those references that could not be eliminated by title or abstract were retrieved and independently reviewed by 2 reviewers (J.T., N.J.). The reviewers were not masked to the title or authors of the publications. Disagreements were resolved by discussion or via a 3rd researcher (H.O.). Abstracts were included only if they contained all the required information. In cases where journal articles contained insufficient information, attempts were made to contact authors to obtain missing details. Reference lists of all retrieved papers were manually searched for potentially eligible papers. Papers from all languages were included; however, these were excluded if a translation could not be made. Theses were not included in this systematic review.

Data extraction and calculations

Data relating to participant characteristics (age, gender, height, mass, aerobic capacity), test conditions (nutritional status prior to testing, type of performance test, exercise protocol, and environmental conditions), intervention characteristics (dose, ingestion schedule), and outcome measures (intensity of performance test and measure of performance in min, kJ, or km) were extracted independently by 2 researchers (J.T., N.J.), with disagreements resolved by discussion or via a 3rd researcher (H.O.). Where necessary, SD was calculated from the reported SEM. For those studies that presented data only graphically, mean and SD were estimated in duplicate using a ruler. One author was contacted and provided mean and SD for data that were reported as median and range.

All beverage and CHO ingestion calculations were independently performed in duplicate (J.T., N.J.) using the ingestion schedule reported in the methods of each manuscript. Some studies reported total beverage or CHO consumption that disagreed with our calculations. For these studies, both values are presented. Rate of beverage ingestion was calculated as the total beverage consumed from 20 min prior to exercise commencement to the end of exercise divided by the duration of exercise. Rate of CHO ingestion was calculated as the rate of beverage ingestion multiplied by the CHO concentration. Mean performance time was used in calculations where the beverage consumption varied with exercise duration. Mean body mass was used in calculations where beverage consumption varied with body mass.

Assessment of methodological quality

The study quality of all studies meeting the inclusion criteria was independently assessed by 2 researchers (J.T., J.R.) using a modified assessment scale created by Downs and Black (7). The researchers were not masked to the title or authors of the publications. Fifteen of the 27 criteria that logically applied to the study designs included in this review were used. Disagreements were resolved by discussion. No studies were eliminated and no additional subgroup analysis was undertaken on the basis of methodological quality.

Analysis

The between-trial mean difference (MD) and 95% CI were calculated for each study. The between-trial standardized MD, or effect size (ES), and 95% CI were also calculated with the Hedges' *g* adjustment for small sample size bias. The pooled, between-participant SD was used in the calculation of the standardized MD. The ES was used as the primary measure of the benefit of CHO ingestion over PLA. The included studies presented data as means and SD (or SEM) for the CHO and the PLA trials, separately. However, this method of presentation is not appropriate for proper analysis of crossover trials (8). Therefore, we imputed the SD of the within-participant differences between CHO and PLA trials. This was achieved by assuming a 0.5 correlation between CHO and PLA. The imputed data were used in the calculation of the SE of the MD or ES and the 95% CI. The 95% CI presented in all tables and figures reflect the imputed SD. The weighted MD for relative change in performance was calculated as the mean of the percentage differences between PLA and CHO trials for each study, weighted according to participant numbers. Between-study variability was examined using the I^2 measure of inconsistency (9). This statistic, expressed as a percentage between 0 and 100, provides a measure of how much of the variability between studies is due to heterogeneity rather than chance. Statistical power was calculated on the basis of detecting a 2% difference in performance between CHO and PLA trials. No assessment of publication bias was undertaken due to there being too few studies within each

performance measure category and potential presence of heterogeneity, both of which affect the robustness of an analysis of publication bias (10).

Meta-analysis. Studies were categorized according to 4 types of performance measures: TTE, TT, submaximal exercise bout followed by TTE (submax+TTE), and submaximal exercise bout followed by TT (submax+TT). All performance results are reported as min, kJ, or km. Published results were converted into the appropriate units where necessary.

Only 1 condition per study was used in the meta-analysis. Where multiple conditions met the eligibility criteria: *1*) the highest CHO concentration meeting the eligibility criteria was selected; *2*) the follicular phase of the menstrual cycle was used; *3*) in studies examining different preexercise fasting periods, the condition closest to 12 h was chosen; *4*) thermoneutral conditions (20–24°C) were selected; and *5*) when multiple types of CHO at the same concentration were used, the condition with the greatest amount of glucose was chosen.

Pooled estimates of the effect of CHO ingestion, using ES, were obtained using a random-effects model. All analyses were conducted using Comprehensive Meta-analysis, version 2 (Biostat) and significance was set at $P < 0.05$.

Two subanalyses, determined a priori, were also conducted: *1*) presence (fasted ≥8 h prior to exercise trials) or absence (nonfasted; up to 6 h postprandial) of an overnight fast (studies were excluded if all or some of the participants fasted for between 6 and 8 h or if some participants fasted and others did not); and *2*) comprehensive diet control for the 24 h prior to testing (either I: participants given food and study used dietary analysis to verify that trials did not differ; or II: use of food records and study used dietary analysis to verify that diet did not differ) compared with the main meta-analysis of all included studies.

Additional subanalyses to clarify the impact of factors known to influence exercise performance were conducted post hoc and were compared with the main analysis. These sub analyses were: *1*) studies with only male participants; *2*) participant training status (inclusive of studies where participant VO_2peak > 50 mL·kg^{-1}·min^{-1} for males and 40 mL·kg^{-1}·min^{-1} for females); *3*) exercise duration (mean reported as >1 and <3 h); and *4*) matched ingestion of electrolytes in CHO and PLA arms.

Sensitivity analysis. A sensitivity analysis, whereby the SD of the within-participant difference was imputed using a range of correlation coefficients, was undertaken to examine the robustness of the use of a presumed 0.5 correlation between CHO and PLA trials.

Results

Identification and selection of studies

The original search netted 41,175 references. After removal of duplicates and elimination of papers based on the eligibility criteria, 50 studies remained (11–60) (**Supplemental Fig. 2**).

Study characteristics

The number of participants in each study ranged from 5 to 19 (**Supplemental Table 1**). Study participants were typically young adult males, with 39 studies exclusively recruiting male participants, 3 studies exclusively recruiting female participants, 7 studies recruiting both males and females, and 1 study where gender was not reported. Mean VO_2peak ranged from 42.8 to 72.0 mL·kg^{-1}·min^{-1}, with 9, 34, and 6 studies including highly trained, trained, and active participants, respectively. Training status was not categorized for 1 study due to the unavailability of VO_2peak data.

Four performance measures were used: *1*) TTE (19 studies) (**Supplemental Table 2**); *2*) submax+TTE (3 studies) (**Supplemental Table 3**); *3*) TT (11 studies) (**Supplemental Table 4**); and *4*) submax+TT (17 studies) (**Supplemental Table 5**). Cycle ergometry was the most common mode of exercise. Prior to testing, participants fasted for between 1 and 21 h, with 26 studies reporting fasting for ≥8 h. For 1 study, we were unable to obtain information on pretest fasting. Diet control on at least the day before testing was established by either food provision in 13 studies or verification via computerized diet analysis in 9 studies. Seventeen studies reported giving a prescribed meal plan or following the same diet for each testing occasion, but this was not verified via diet records. Eleven studies reported no formal dietary control.

Fluid ingestion protocols are summarized in **Supplemental Tables 6–9**. All studies delivered either CHO or PLA at regular intervals in the same volumes throughout exercise. Ten studies included a preexercise bolus 5–20 min before exercise, 22 studies delivered the first bolus at the start of exercise, and the remaining 18 did not deliver fluid prior to exercise. A masked PLA drink (48 studies) or capsules (2 studies) was used in all studies with the intention of making participants unaware of the treatments, although 2 studies did not state that the treatment was delivered in such a manner. The remaining studies reported using either a double- (38 studies) or single-blind (10 studies) protocol.

Methodological quality

The scores for the assessment of methodological quality ranged from 10 to 12 of 15 items (67–80%) (**Supplemental Table 10**). The main points of discrepancy between studies were with the use of blinding of participants and researchers and with the provision of exact *P*-values. Additionally, all but 1 study did not provide a clear description of participants using inclusion/exclusion criteria and no study recruited a representative sample.

Study outcomes

All studies provided sufficient data to enable calculation of MD, ES, and 95% CI (**Supplemental Tables 11–14**). For TT, 3 of the 11 studies reported significant ES, ranging from 0.52 to 1.45. For submax+TT, 11 of the 22 ES that were calculated from 17 studies were significant (ES range: 0.57–1.61). For TTE, 7 of the 22 ES that were calculated from 19 studies were significant (ES range: 0.70–1.03). For submax+TTE, 1 of the 3 studies reported a significant ES.

Effect of CHO ingestion on performance (meta-analysis)

TTE. The effect of CHO ingestion in TTE studies is summarized in **Supplemental Table 11** and **Fig. 1**. There was a significant pooled ES (ES from 19 studies = 0.47; 95% CI = 0.32–0.62; $P < 0.001$). There was no evidence of heterogeneity among the studies ($I^2 = 0.0\%$; $P = 0.49$). The weighted mean performance improvement was 15.1%.

Submaximal exercise + TTE. Three studies used submax +TTE designs (**Supplemental Table 12** and **Fig. 2**) and there was a significant pooled ES (ES 0.44; 95% CI = 0.08–0.80; $P = 0.017$). There was no evidence of heterogeneity among the studies ($I^2 = 0.0\%$; $P = 0.52$). The weighted mean improvement in performance was 54.2%.

TT. The effect of CHO ingestion in TT studies is summarized in **Supplemental Table 13** and **Fig. 3**. There was a significant pooled ES (ES from 11 studies = 0.30; 95% CI = 0.07–0.53; $P = 0.011$) and a weighted mean performance improvement of 2.0%. There was evidence of heterogeneity among studies ($I^2 = 43.6\%$; $P = 0.06$), although this was not significant. Further examination of the TT studies showed that 1 study was an outlier (41) with a much larger ES. This was likely due to a

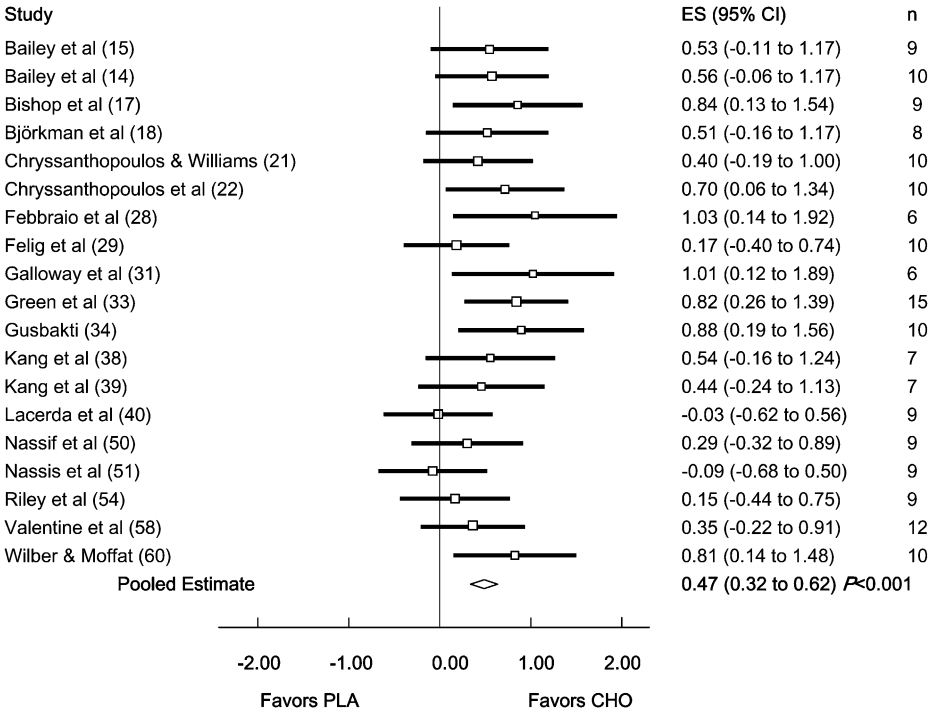

FIGURE 1 Forest plot for TTE studies (19 studies). Graph depicts ES and 95% CI for individual studies and the pooled estimate.

longer TT distance being undertaken and with consistent performances among participants. Therefore, the mean time taken to complete the TT was longer than in other studies, but the SD was relatively small. After reanalysis with this study (41) removed, there was still a significant pooled ES (ES from 10 studies = 0.21; 95% CI = 0.03–0.39; $P = 0.023$) and there was no evidence of heterogeneity among the remaining studies (I^2 = 0.0%; $P = 0.62$).

Submaximal exercise + TT. The effect of CHO ingestion in submax+TT studies is summarized in **Supplemental Table 14** and **Fig. 4**. There was a significant pooled ES (ES from 17 studies = 0.53; 95% CI = 0.37–0.69; $P < 0.001$) and the weighted mean performance improvement was 7.5%. There was some heterogeneity among the studies (I^2 = 6.0%; $P = 0.38$), although this was not significant.

Sensitivity analysis. The repeat meta-analyses using different correlation coefficients yielded similar pooled ES and 95% CI (**Supplemental Table 15**), suggesting that the use of a presumed 0.5 correlation between CHO and PLA trials is robust.

Subanalysis: I/II diet control. The magnitude of the ES was similar for studies using a strict preexercise diet control compared with main analysis. ES, 95% CI, and the number of studies in each subcategory are presented in **Supplemental Table 16**

Subanalysis: ≥8 h fast vs. <6 h fast. The magnitude of the ES was similar for studies where participants fasted for ≥8 or <6 h. ES, 95% CI, and the number of studies for this subanalysis are presented in **Supplemental Table 17**.

Post hoc subanalysis. Subanalysis of studies with only male or trained and highly trained participants, exercise duration of >1 and <3h, and those with matched electrolytes for the CHO and PLA arms is summarized in **Supplemental Table 18**. The magnitudes of the ES were similar for all comparisons.

Discussion

This systematic review thoroughly assessed evidence regarding the performance effect of CHO ingestion not exceeding 8% and between 30 and 80 g/h compared with PLA for endurance exercise ≥ 1 h. Several important features make this systematic review novel: included studies had robust research designs, i.e. single- or double-blinded, randomized, PLA-controlled trials; evidence from the earliest record to January 2011 from a wide

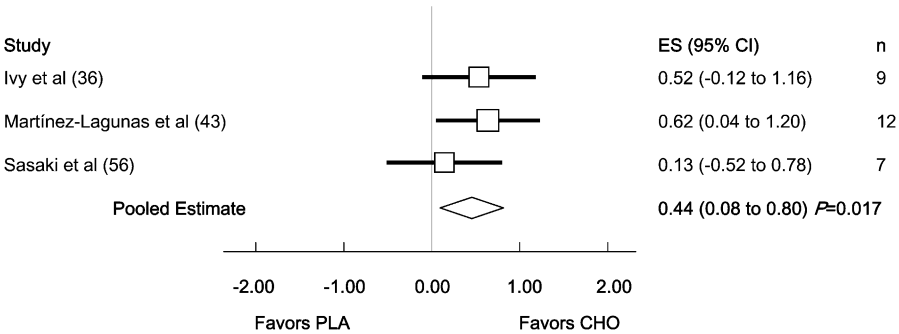

FIGURE 2 Forest plot for submax+TTE studies (3 studies). Graph depicts ES and 95% CI for individual studies and the pooled estimate.

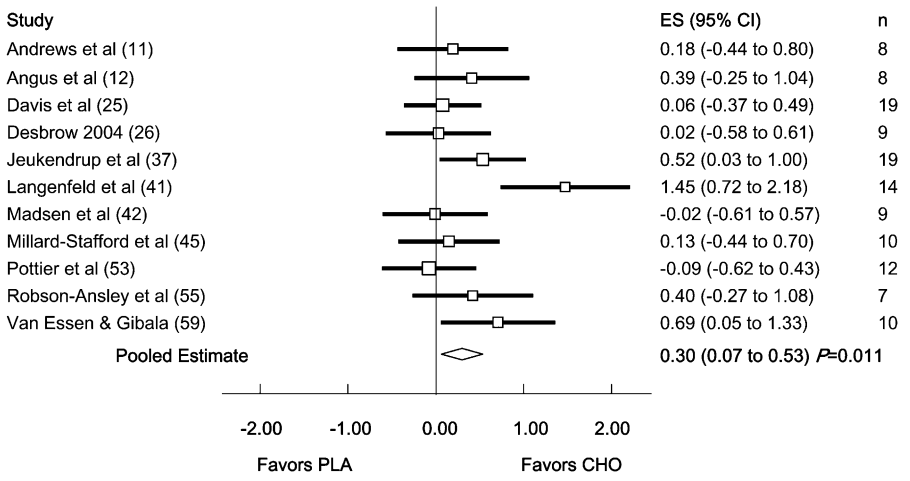

FIGURE 3 Forest plot for TT studies (11 studies). Graph depicts ES and 95% CI for individual studies and the pooled estimate.

range of relevant databases was evaluated; beverage CHO composition (5–8%) and ingestion dose (30–80 g/h CHO) were similar across studies and consistent with current recommendations (4,5); and analysis was partitioned according to performance measure used, as the ergogenic effect of CHO ingestion was not assumed to be consistent across testing modalities (TTE, TT, submax+TTE, or submax+TT), which are known to measure different aspects of physical performance and also vary widely with respect to the CV (61). Given all of the included studies had small sample sizes and that many were insufficiently powered to individually detect significant differences (power to detect a 2% difference in studies with TT or submax+TT ranged from 3 to 40%), the use of meta-analysis enabled a more precise estimate of the performance effect of CHO ingestion. The pooled ES, favoring CHO ingestion, were significant for all performance protocols. The weighted mean performance differences between CHO and PLA favored CHO ingestion for improving exercise performance for all test conditions, ranging from 2.0% improvement for TT to 54.2% for submax+TTE tests. Findings were similar and consistent when participants fasted (≥8 h) or were fed a preexercise meal (<6-h fast). A benefit of CHO ingestion on performance was also evident, irrespective of whether dietary intake had been strictly controlled in the 24-h preceding exercise. These results suggest that the ergogenic effect of exogenous CHO ingestion during exercise is sufficiently powerful to improve performance even when individuals optimize endogenous CHO availability prior to exercise. Post hoc analysis showed the trends across the different performance tests with ingestion of 30–80 g/h CHO remained for studies using only male or trained and highly trained participants and for studies where mean exercise duration was between 1 and 3 h or electrolyte ingestion was matched between CHO and PLA conditions.

The studies included in this review employed a wide range of test protocols to measure exercise performance. We observed a significant effect of CHO ingestion with TTE; however, the TTE protocol has poorer reliability (>10% CV) and limited application to athletic performance due to factors such as exercise duration (longer bouts are associated with increased CV), participant motivation, and feedback (61). Twenty-eight of

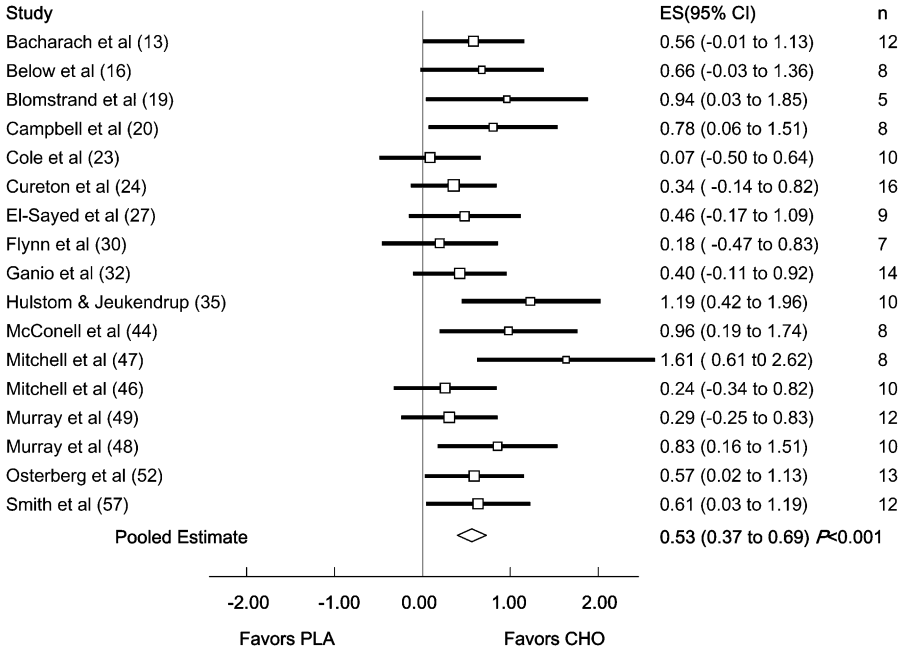

FIGURE 4 Forest plot for submax+TT (17 studies). Graph depicts ES and 95% CI for individual studies and the pooled estimate.

the 50 included studies used either TT or submax+TT. Compared with TTE tasks, these tests more closely mimic real competitive endurance events, better reflect real-world performance, and typically have superior reliability (<5% CV) (61). In this review, studies employing TT and submax+TT protocols showed significant pooled ES. When considered as a relative difference, CHO ingestion was associated with a weighted mean improvement of 2.0% for TT and 7.5% for submax+TT. Given the low number of studies using highly trained participants and heterogeneity of TT tasks employed, we are precluded from making definitive statements about the magnitude of effect of CHO ingestion with reference to the smallest worthwhile improvement in performance. Yet these outcomes suggest meaningful real-world applicability and in elite sporting contexts, even minor improvements can change the outcome of an event. For example, on the basis of studies measuring TT performance in highly trained cohorts (12,13,19,26,37,44), improvement with CHO ingestion was comparable to the 2.7% difference between first and 5th places at the World TT Cycling Championships from 2000 to 2009 (62–71).

The precise mechanism supporting the ergogenic benefit of CHO ingestion remains unclear. Early reports attributed the benefit to the maintenance of euglycemia (72) and/or sparing of muscle glycogen (73,74). Although there is little support for a direct effect on muscle glycogen sparing (75), exogenous CHO ingestion may attenuate hepatic glycogen degradation (76,77). This review shows that ingestion of up to 80 g/h CHO is ergogenic and, depending on the sport, athlete size and mix of CHO ingested, higher rates of ingestion may be beneficial. Use of different sugar types within a beverage has been linked with higher rates of intestinal absorption (via activation of different intestinal transporters) and CHO oxidation (peak exogenous CHO oxidation of ~1.5–1.75 g/min) during exercise (78–80). Despite the apparent benefit of higher rates of CHO ingestion (>80 g/h) with multiple sugar types, such studies (78–82) were not included in this review, because they were outside the range we examined, i.e. that which is consistent with current recommendations (4,5) for CHO ingestion. The few studies that have assessed performance benefits with CHO ingestion > 80 g/h (83–86) show performance enhancement at this elevated level of CHO ingestion. Several studies have also shown that ingestion of even relatively small amounts of exogenous CHO is associated with maintenance of euglycemia (87), with a possible central nervous system-mediated benefit independent of CHO dose. Such an ergogenic effect may in part reflect enhanced central drive via a sensory mechanism associated with receptors in the mouth and/or gastrointestinal tract and studies reporting a significant performance improvement after use of a CHO "mouth-wash" support this hypothesis (53,88,89), although this has not been demonstrated in all studies (90).

Limitations. A limitation associated with the meta-analysis conducted in this review was that subanalyses for parameters known to influence exercise performance such as environmental conditions were not undertaken. Whereas the ergogenic benefit of CHO ingestion is known to be influenced by environmental conditions, the heterogeneity of this parameter in the studies prohibited subanalysis. There is a strong gender bias in the studies to recruitment of men aged 18–35 y and trained or highly trained participants, so the results may be not be generalizable to women, older men, or untrained individuals. An additional limitation is that it is possible that not all relevant papers were retrieved. Excluded keywords may have eliminated relevant papers not identified from searching reference lists of retrieved papers. Additionally, 4 manuscripts were unable to be retrieved and insufficient information from a further 3 resulted in 7 potentially eligible manuscripts being eliminated.

In conclusion, this systematic review indicates that ingestion of CHO consistent with current recommendations at a rate of 30–80 g/h (typically from CHO-electrolyte beverages at concentrations of 6–8%) during endurance exercise of at least 1 h improves TT, TTE, submax+TT, and submax+TTE performance. Although the mechanism underpinning this improvement is not clearly understood, the mean performance improvement of 2.0, 15.1, 7.5, and 54.2%, respectively, would be expected to translate into a meaningful competitive advantage for highly trained athletes. Recent evidence supports that the ergogenic benefit may extend beyond 80 g/h CHO when multiple transportable CHO are consumed and this research deserves consideration when current recommendations are reviewed. The benefit and practicality of other exogenous CHO strategies, including the use of CHO as a mouth wash for either training or competition, should also be considered.

Acknowledgments

J.T. and J.R. conducted quality assessment; J.T., J.R., and C.B. conducted meta-analyses and tabulated data; and J.T. and N.J. conducted the literature search and data extraction. All authors participated in the design of the study (except C.B.) and interpretation of data and contributed to the drafts of the manuscript. All authors read and approved the final version of the manuscript.

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