# The Influence of Drinking Fluid on Endurance Cycling Performance: A Meta-Analysis 

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#### Abstract

Background Fluid replacement during cycling exercise evolves on a spectrum from simply drinking to thirst to planned structured intake, with both being appropriate recommendations. However, with mixed findings suggesting fluid intake may or may not improve endurance cycling performance (ECP) in a diverse range of trained individuals, there is a clear need for summarised evidence regarding the effect of fluid consumption on ECP. Objectives (1) Determine the magnitude of the effect of drinking fluid on performance during cycling exercise tasks of various durations, compared with no drinking; (2) examine the relationship between rates of fluid intake and ECP; and (3) establish fluid intake recommendations based on the observations between rates of fluid intake and ECP. Study Design Meta-analysis. Methods Studies were located via database searches and cross-referencing. Performance outcomes were converted to a similar metric to represent percentage change in power output. Fixed- and random-effects weighted mean effect


[^0]summaries and meta-regression analyses were used to identify the impact of drinking fluid on ECP.
Results A limited number of research manuscripts ( $n=9$ ) met the inclusion criteria, producing 15 effect estimates. Meta-regression analyses demonstrated that the impact of drinking on ECP under $20-33^{\circ} \mathrm{C}$ ambient temperatures was duration-dependent. Fluid consumption of, on average, $0.29 \mathrm{~mL} / \mathrm{kg}$ body mass $/ \mathrm{min}$ impaired 1 h high-intensity ( $80 \%$ peak oxygen uptake $\left[\dot{\mathrm{Vo}}_{2 \text { peak }}\right]$ ) ECP by $-2.5 \pm 0.8 \%$ ( $95 \%$ confidence interval [CI] -4.1 to $-0.9 \%$ ) compared with no fluid ingestion. In contrast, during $>1$ to $\leq 2 \mathrm{~h}$ and $>2 \mathrm{~h}$ moderate-intensity $\left(60-70 \% \dot{\mathrm{~V}}_{2}{ }_{2 \text { peak }}\right)$ cycling exercise, ECP improved by $2.1 \pm 1.5 \%$ ( $95 \%$ CI $1.2-2.9 \%$ ) and $3.2 \pm 1.2 \% ~(95 \%$ CI $0.8-5.6 \%)$, respectively, with fluid ingestion compared with no fluid intake. The associated performance benefits were observed when the rates of fluid intake were in the range of $0.15-0.20 \mathrm{~mL} / \mathrm{kg}$ body mass $/ \mathrm{min}$ for $>1$ to $\leq 2 \mathrm{~h}$ cycling exercise and ad libitum or $0.14-0.27 \mathrm{~mL} / \mathrm{kg}$ body mass $/ \mathrm{min}$ for cycling exercise $>2 \mathrm{~h}$.
Conclusions A rate of fluid consumption of between 0.15 and $0.34 \mathrm{~mL} / \mathrm{kg}$ body mass $/ \mathrm{min}$ during high-intensity 1 h cycling exercise is associated with reductions in ECP. When cycling at moderate intensity for $>1$ to $\leq 2 \mathrm{~h}$, cyclists should expect a gain in performance of at least $2 \%$ if fluid is consumed at a rate of $0.15-0.20 \mathrm{~mL} / \mathrm{kg}$ body mass $/ \mathrm{min}$. For cycling exercise $>2 \mathrm{~h}$ conducted at moderate intensity, consuming fluid ad libitum or at a rate of $0.14-0.27 \mathrm{~mL} / \mathrm{kg}$ body mass/min should improve performance by at least $3 \%$. Until further research is conducted, these recommendations should be used as a guide to inform hydration practices.

## Key Points

The primary finding of this meta-analysis was that the effect of fluid consumption on endurance cycling performance (ECP) is complex and needs to be considered in the context of the exercise task and its associated demands.

Exercise duration was identified as a key factor that distinguished between the positive and negative effects of fluid ingestion on ECP. During 1 h highintensity exercise, ECP decreased by $2.5 \%$ when fluid was consumed at high rates $(0.15-0.34 \mathrm{~mL} / \mathrm{kg}$ body mass $/ \mathrm{min}$ ), compared with no fluid intake. However, performance improvements of 2.1 and $3.2 \%$ were observed when fluid was consumed during moderate-intensity cycling exercise of $>1$ to $\leq 2 \mathrm{~h}$ and $>2 \mathrm{~h}$ duration, respectively.
To optimise ECP, cyclists should avoid consuming fluids at a rate of between 0.15 and $0.34 \mathrm{~mL} / \mathrm{kg}$ body mass/min during high-intensity exercise of 1 h , but should consume $0.15-0.20 \mathrm{~mL} / \mathrm{kg}$ body mass $/ \mathrm{min}$ of fluid during exercise of $>1$ to $\leq 2 \mathrm{~h}$, and drink ad libitum or consume $0.14-0.27 \mathrm{~mL} / \mathrm{kg}$ body mass/ $\min$ for exercise duration $>2 \mathrm{~h}$.

## 1 Introduction

Goulet [1, 2] meta-analytically identified that dehydration of up to $4 \%$ body mass loss does not impair endurance cycling performance (ECP). However, based on the numerous physiological and psychological benefits of fluid ingestion during exercise, it is unreasonable to expect cyclists not to consume fluid during an event where anticipated dehydration will be $<4 \%$ of body mass. In fact, consuming fluid during cycling exercise offers benefits of lower perceived exertion, decreased thirst sensation, reduced cardiovascular and thermal stress, and enhanced substrate utilisation compared with no fluid ingestion [3, 4]. Moreover, stimulation of the pharyngeal receptors with a trivial amount of fluid ingestion $(100 \mathrm{~mL})$ has been shown to improve endurance cycling capacity compared with mouth rinsing only or no fluid intake [5]. The authors speculated that the act of swallowing fluid and the subsequent cooling sensation in the digestive tract may be enough of a motivational factor to promote improved performance. Independent of the causal factor(s), this observation suggests that the simple act of drinking fluid
during cycling exercise may benefit performance and that the perception of drinking fluid may be as, if not more, important for athletes than the absolute volume consumed during exercise.

The current American College of Sports Medicine (ACSM) position stand on exercise and fluid replacement highlights that the amount and rate of fluid replacement depends on the individual sweating rate, exercise duration and opportunities to drink [3]. Additionally, the guidelines suggest that longer exercise durations lead to a disproportionate balance between fluid replacement and requirements, leading to dehydration [3]. This is also indicated in endurance cycling tasks that are $>1 \mathrm{~h}$, with a stronger negative association between changes in cycling power output and exercise duration in comparison to exerciseinduced dehydration [1]. Thus, with the potential for ECP to be relatively well-maintained despite a mismatch between the rates of fluid intake and sweat losses during cycling exercise durations $<1 \mathrm{~h}[6-8]$, but not necessarily during longer exercise [9, 10], it is plausible that fluid ingestion may offer an ECP benefit that is duration-dependent. To the best of our knowledge, no meta-analysis has yet attempted to quantify the effect of fluid ingestion on performance during cycling tasks of various durations. Moreover, we are not aware of any meta-analysis that has evaluated whether a possible relationship between rates of fluid intake and ECP exists.

Strategies for fluid replacement during cycling exercise are comprised within a large spectrum and may range from purely relying on thirst sensation [11] to customised fluid ingestion plans based on the estimation of sweat losses, usually with the aim of preventing a body mass loss $>2 \%$ [3]. A major limitation of the reliance on thirst sensation to gauge fluid intake is that under certain circumstances (e.g. psychological stress, repeated acute food intake, cold temperature, various medications, older athletes) [11], thirst may not be a reliable indicator of fluid needs, which may lead to suboptimal fluid intake and ECP. Moreover, some individuals may simply be reluctant to rely on thirstrelated sensations to guide their intake of fluid during cycling exercise [11]. On the other hand, customised individual plans require athletes to estimate sweat losses during a particular cycling task with respect to exercise intensity and environmental conditions; however, this may not always be practical, as underlined by the ACSM [3]. Given these limitations, it would helpful for those individuals to be able to rely on evidence-based, practical recommendations providing guidance on the optimal rates of fluid intake during cycling exercise of various durations.

The goal of this meta-analysis was threefold: (1) determine the magnitude of the effect of drinking fluid on performance during cycling exercise of various durations; (2) examine the relationship between rates of fluid intake
and ECP; and (3) provide guidelines on the optimal rates at which cyclists should be drinking while exercising to optimise performance. The results of the present metaanalysis will assist coaches, cyclists and health professionals with regard to optimal rates of fluid intake during cycling exercise.

## 2 Methods

### 2.1 Data Sources

The process used for selecting research articles is outlined as a process flowchart in Fig. 1. A systematic search of the PubMed (MEDLINE) (http://www.ncbi.nlm.nih.gov/ pubmed), Scopus (http://www.scopus.com/) and Web of Science (http://apps.webofknowledge.com/) online databases, with no date limitation, was conducted using the following keywords (alone or in combination): 'hydration', 'dehydration', 'hypohydration', 'rehydration', 'hyperhydration', 'fluid balance', 'fluid consumption', 'endurance performance', 'exercise capacity' and 'exercise performance'. Articles that pertained to fluid ingestion and ECP were identified. When a potential article was found, the title and abstract were read by the first author. If the abstract revealed that an intervention was made to determine the effect of exercise-induced hypohydration and/or fluid ingestion on ECP, then the entire article was read by the first author to determine eligibility. In the event of inclusion discrepancies, these were resolved by a review from the third and fourth authors. Reference lists from retrieved articles, as well as published articles [2] were further examined to identify additional articles for potential inclusion. Case studies, conference proceedings, published abstracts, dissertations and manuscripts published in non-peer-reviewed journals were excluded. Only English-written articles were considered during the research process. The last day of the search was performed on 11 April 2015. The Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines were followed during the preparation of this review and presentation of the results [12].

### 2.2 Inclusion and Exclusion Criteria

The following inclusion criteria were used to identify articles qualifying for this meta-analysis: (1) participants were healthy adults (men or women) aged $\geq 18$ years; (2) the study included a control group that did not drink during exercise; (3) fluid replacement was administered orally; (4) hypohydration was induced during exercise, not before; (5) the study was laboratory-controlled and cycling-related; (6) the performance measure involved continuous cycling
exercise $>2 \mathrm{~min}$; (7) data needed to calculate percentage changes in power outputs, effect estimates and variances were provided; (8) percentage body mass losses were reported; and (9) nutrient intake was matched between experimental groups. An article was excluded if it presented with either of the following criteria: (1) no measured performance outcome; and (2) participants were unable to complete the entire exercise protocol, as a priori defined.

### 2.3 Data Extraction

Coding sheets with operational definitions were developed and utilised for this investigation. When necessary, authors were contacted to resolve ambiguities and issues with methodology or findings. Coded variables included (1) study characteristics; (2) participant physical and fitness characteristics; (3) exercise protocol characteristics; (4) fluid intakes during exercise and hypohydration levels; and (5) exercise performance.

### 2.4 Exercise Protocol Characteristics

Exercise duration represents the mean total exercise time (min) completed in the 'no fluid intake' and 'fluid intake' groups [1]. Exercise intensity represents the mean relative peak oxygen consumption $\left(\dot{\mathrm{V}}_{\text {2peak }}\right)$ at which the exercise protocols (i.e. the no fluid and fluid intake groups) were conducted. A weighted average technique was used to determine the exercise intensity of studies that combined multiple bouts of exercise conducted at different intensities. Studies by Dugas et al. [9] and Kay and Marino [7] did not indicate the percentage of $\dot{V}_{2 \text { peak }}$ at which the exercise protocols were conducted, therefore exercise intensity was computed as explained by Goulet [2].

### 2.5 Fluid Consumption and Hypohydration Level

Fluid consumption represents the entire amount of fluid consumed over the total duration of exercise. Any fluid consumed within the 5 min period prior to the start of exercise was included in the computation of total fluid consumption as this fluid was integrated into the body during exercise and contributed to physiological regulation [13, 14]. The rate of fluid consumption ( $\mathrm{mL} / \mathrm{kg}$ body mass $/ \mathrm{min}$ ) was calculated by dividing the overall fluid consumed ( mL ) during a given exercise trial by pre-exercise body mass ( kg ) and then by the total exercise time (min). Hypohydration level was taken as the percentage change in body mass from pre- to post-exercise. It is acknowledged that assessment of hypohydration using changes in body mass lacks precision; however, under field conditions, it is the most practical and reliable method of estimating hypohydration level [15].


Fig. 1 Selection process used for the inclusion and exclusion of articles for this meta-analysis

### 2.6 Exercise Performance

Five studies $[6-9,13]$ used a time-trial-type exercise protocol to test ECP, with all reporting mean maintained power output during exercise. Hence, in these studies, the percentage change in cycling performance was measured using the formula shown in Eq. 1:
((Fluid intake group mean power output

- no fluid intake group mean power output)
/no fluid intake group mean power output) $\times 100$

Four studies [10, 14, 16, 17] used a fixed-power output test to exhaustion to evaluate the impact of fluid intake on ECP. To make results comparable among all studies included in this meta-analysis, the percentage changes in endurance cycling capacity were transformed to equivalent changes in performance during a time-trial-type exercise, according to Eq. 2: [2]
(((Fluid intake group mean time to exhaustion

- no fluid intake group mean time to exhaustion
$/$ no fluid intake group mean time to exhaustion) $\times 100$ )
$/\left(\% \dot{V}_{\text {O2peak }}\right.$ at which the test was performed $\left./ 6.4\right)$


### 2.7 Statistical Analysis

Data were analysed using Microsoft Office Excel 2007, version 12.0.6735.5000 (Microsoft Corporation, Redmond, WA, USA), IBM SPSS Statistics, version 21.0.0.0 (IBM Corporation, Armonk, NY, USA) and Comprehensive Meta-Analysis (CMA), version 2.2.064 (CMA, Englewood, NJ, USA) software, along with SPSS macros developed by Lipsey and Wilson [18].

### 2.7.1 Weighted Mean Effect Summary

A weighted mean effect summary including $>10$ studies was computed using a random-effects model, whereas when the number of studies was $\leq 10$, the weighted mean effect summary was computed using a fixed-effect model. This procedure was followed because when the number of studies is small, the estimate of the between-study variance to be used with a random-effects model has poor precision. When possible, variances were directly calculated from the reported $\Delta$ standard errors or standard deviations of the net percentage changes in cycling performance. When differences between groups were not reported, variances were computed from reported $p$ values or confidence intervals (CI), and, when neither were reported, from $p$ values equal to $X$, where $X$ is any $p$ value $\leq 0.05$ [19]. When only $p>0.05$ was reported, individual variances for net percentage changes in cycling performance were estimated with the formula used by the CMA software, using an imputed correlation coefficient [19] of 0.68 computed from the raw experimental results of six individual studies provided by two researchers [8, 9]. Several research articles included more than one treatment effect. To account for independency of research data, two separate statistical analyses were performed where, on one occasion, the weighted mean effect summary was determined, with only one effect estimate and weighting factor per research article (representing the mean effect estimate and weighting factor of all studies included in the research article), and, on the other occasion, where each outcome was treated independently. If both approaches yielded similar figures then the model treating each outcome independently was retained since it provides a greater level of information. Qualitative interpretation of the practical significance of the effect of fluid intake on cycling performance under real-world conditions was computed using the spreadsheet developed by Hopkins [20]. The smallest worthwhile percentage change in power output was determined for long-distance cyclists and set at $1.6 \%$ [1]. For each performance outcome, the normality of data distribution was verified using the Shapiro-Wilk test. Results are reported as means $\pm$ standard errors.

### 2.7.2 Evaluation of Heterogeneity and Publication Bias

Heterogeneity and publication bias were determined only when a weighted mean effect summary was derived from $>10$ studies. Between-study heterogeneity was assessed using the $I^{2}$ statistic and the Cochran $Q$ test, with $p \leq 0.01$ indicating significance [21]. Whether there was evidence of literature bias was examined with a funnel plot visual inspection, and statistically tested using Egger's test of the intercept [21]. The Orwin's fail-safe N procedure was used to test if the overall observed weighted mean treatment effect was an artifact of bias [21], with the smallest worthwhile percentage change in power output brought about by drinking taken as $1.6 \%$ [2]. Finally, the potential impact of bias was estimated using the trim and fill technique [21].

### 2.7.3 Meta-Regression Analysis

Meta-regressions including $>10$ data points were performed using a restricted maximum likelihood randomeffects model. When the number of studies was $\leq 10$, the meta-regressions were computed using a fixed-effect model. Categorical variables were dummy-transformed with $\mathrm{k}-1$, where k is the number of levels of the original variable. Multiple regression analyses were examined for the presence of multicollinearity between predictor variables (variance inflation factor). The alpha level for statistical significance was set at $p \leq 0.05$.

## 3 Results

### 3.1 Search Results

The initial database search identified 15,532 unique records. After screening the titles, a total of 483 articles were identified that were potentially related to the topic of investigation and their abstracts were subsequently read. Of these, 151 articles potentially matched the inclusion criteria and fulltext articles were read. Nine articles met all the inclusion criteria [6-10, 13, 14, 16, 17]. Figure 1 details the search procedure and reasons for exclusion after full-text extraction. Two separate studies were performed within McConell et al. [10], McConell et al. [8] and Kay and Marino [7], while four separate studies were included within Dugas et al. [9], yielding a total of 15 individual studies. Table 1 provides a detailed description of participant characteristics, exercise protocols, and rates of fluid intake and hypohydration levels of each included research manuscript and individual study, which were classified according to exercise duration, i.e. 1 h , $>1$ to $\leq 2 \mathrm{~h}$ and $>2 \mathrm{~h}$.
Table 1 Exercise protocol characteristics, rates of fluid intake and hypohydration levels of included research manuscripts and individual studies

| References (alphabetical order) | No. of participants; sex; and age (years) | Exercise protocol | Exercise duration (min) and intensity <br>  | Ambient temperature $\left({ }^{\circ} \mathrm{C}\right)$ | Relative humidity (\%) | Fluid intake ( $\mathrm{mL} / \mathrm{min}$ and $\mathrm{mL} / \mathrm{kg}$ body mass $/ \mathrm{min}$ ) | Dehydration level (\% body mass) |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Exercise duration of 1 h |  |  |  |  |  |  |  |
| Bachle et al. [6] | 10 recreationally-trained participants; 4 men, 6 women; $29 \pm 6$ | Fixed-duration, self-paced time trial | 60 and 61 | 21 | 72 | 20 and 0.30 | $\begin{aligned} & \text { NFI group: }-1.0 \\ & \text { FI group: }+0.8 \end{aligned}$ |
| Kay and Marino [7] | $\begin{aligned} & 7 \text { healthy cyclists; } 6 \text { men, } 1 \\ & \text { woman } 21 \pm 3 \end{aligned}$ | Fixed-duration, self-paced time trial | 60 and 80 | Moderate: FI group vs. NFI group: 19.8; Warm: FI group vs. NFI group: 33.2 | 63 | Moderate: 22 and 0.29 <br> Warm: 25 and 0.34 | $\mathrm{A}^{\mathrm{a}}$ <br> Moderate: <br> NFI group: -1.8 <br> FI group: 0 <br> $B^{a}$ <br> Warm: <br> NFI group: - 2.2 <br> FI group: 0 |
| McConell et al. [8] | 8 well-trained cyclists and triathletes; 8 men, 0 women; $26 \pm 3$ | 1. Fixed-intensity $+$ <br> 2. Fixed-duration time trial | $\begin{aligned} & 1: 45 \text { and } 85 \\ & \text { 2: } 15 \text { and } 81 \end{aligned}$ | 21 | 41 | FR-50 <br> 12 and 0.15 <br> FR-100 <br> 25 and 0.31 | $1 \mathrm{~A}^{\mathrm{a}}$ <br> FR-50: <br> NFI group: -1.9 <br> FI group: -1.0 <br> $1 \mathrm{~B}^{\mathrm{a}}$ <br> FR-100 <br> NFI group: -1.9 <br> FI group: 0 |
| Robinson et al. [13] | 8 endurance-trained participants; 8 men, 0 women; $26 \pm 4$ | Fixed-duration, self-paced time trial | 60 and 85 | 20 | 60 | 25 and 0.32 | NFI group: -2.3 <br> FI group: -0.9 |
| Mean $\pm$ SD | $8 \pm 1$ | - | $\begin{gathered} 60 \pm 0 \text { and } \\ 78 \pm 10 \end{gathered}$ | $23 \pm 5$ | $57 \pm 13$ | $\begin{aligned} & 21 \pm 5 \text { and } \\ & 0.29 \pm 0.07 \end{aligned}$ | NFI group: $-1.9 \pm 0.5$ <br> FI group: $-0.2 \pm 0.7$ |
| Exercise duration $>1$ to 2 h |  |  |  |  |  |  |  |
| Maughan et al. [16] | 12 healthy participants; 12 men, 0 women; $24 \pm 3$ | Fixed-intensity to exhaustion | 93.5 and 70 | 21 | 21 | 11 and 0.16 | NFI group: -1.9 <br> FI group: -0.6 |
| Maughan et al. [17] | 6 healthy participants; 6 men, 0 women; $29 \pm 5$ | Fixed-intensity to exhaustion | 73.2 and 70 | 22.5 | 45 | 10 and 0.15 | NFI group: -1.8 <br> FI group: -0.7 |
| Walsh et al. [14] | 6 endurance-trained competitive cyclists or triathletes; 6 men, 0 women; $26 \pm 4$ | 1. Fixed-intensity $+$ <br> 2. Fixed-intensity to exhaustion | $\begin{aligned} & 1: 60 \text { and } 70 \\ & 2: 8 \text { and } 90 \end{aligned}$ | 32 | 60 | 14 and 0.20 | $\begin{aligned} & \text { NFI group: }-1.8 \\ & \text { FI group: }-0.2 \end{aligned}$ |

Table 1 continued

| References (alphabetical order) | No. of participants; sex; and age (years) | Exercise protocol | Exercise duration (min) and intensity (\%) $\dot{\mathrm{O}}_{\text {2peak }}$ ) | Ambient temperature $\left({ }^{\circ} \mathrm{C}\right)$ | Relative humidity (\%) | Fluid intake ( $\mathrm{mL} / \mathrm{min}$ and $\mathrm{mL} / \mathrm{kg}$ body mass $/ \mathrm{min}$ ) | Dehydration level (\% body mass) |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Mean $\pm$ SD | $8 \pm 3$ | - | $\begin{gathered} 78 \pm 13 \text { and } \\ 71 \pm 2 \end{gathered}$ | $25 \pm 5$ | $42 \pm 20$ | $\begin{aligned} & 12 \pm 2 \text { and } \\ & 0.17 \pm 0.03 \end{aligned}$ | NFI group: $-1.8 \pm 0.1$ <br> FI group: $-0.5 \pm 0.3$ |
| Exercise duration $>2 \mathrm{~h}$ |  |  |  |  |  |  |  |
| Dugas et al. [9] | 6 highly-trained cyclists; 6 men, 0 women; $23 \pm 4$ | Time trial | 127 and 52 | 33 | 50 | $100 \%$ : 22 and 0.32 <br> $66 \%$ : 14 and 0.21 <br> $33 \%$ : 7 and 0.10 <br> Ad lib: 11 and 0.16 | $\mathrm{A}^{\mathrm{a}}$ <br> 100\% <br> NFI group: -4.3 <br> FI group: -0.5 <br> $B^{a}$ <br> 66\% <br> NFI group: -4.3 <br> FI group: $\mathbf{- 1 . 9}$ <br> $\mathrm{C}^{\mathrm{a}}$ <br> 33\% <br> NFI group: -4.3 <br> FI group: -2.9 <br> $\mathrm{D}^{\mathrm{a}}$ <br> Ad lib <br> NFI group: -4.3 <br> FI group: - 2.1 |
| McConell et al. [10] | 7 well-trained cyclists and triathletes; 7 men, 0 women; $24 \pm 3$ | 1. Fixed-intensity $+$ <br> 2. Fixed-intensity to exhaustion | $\begin{aligned} & \text { 1: } 120 \text { and } 70 \\ & \text { 2: } 4 \text { and } 90 \end{aligned}$ | 21 | 43 | FR-50: 9 and 0.14 <br> FR-100: 19 and 0.27 | $2 \mathrm{~A}^{\mathrm{a}}$ <br> FR-50 <br> NFI group: -3.2 <br> FI group: -1.8 <br> $2 \mathrm{~B}^{\mathrm{a}}$ <br> FR-100 <br> NFI group: - 3.2 <br> FI group: -0.1 |
| Mean $\pm$ SD | $7 \pm 1$ | - | $\begin{gathered} 126 \pm 2 \text { and } \\ 58 \pm 10 \end{gathered}$ | $29 \pm 6$ | $48 \pm 4$ | $14 \pm 6$ and $0.20 \pm 0.08$ | NFI group: $-3.9 \pm 0.6$ <br> FI group: $-1.6 \pm 1.1$ |

 replacement, $66 \% 66 \%$ fluid replacement, $33 \% 33 \%$ fluid replacement, $S D$ standard deviation
${ }^{\text {a }}$ Corresponds to the studies found in the forest plot


Fig. 2 Forest plot demonstrating the impact of fluid intake on overall cycling performance. CI confidence interval, filled diamond represents the overall weighted mean treatment effect. Sizes of the squares
are proportional to the weight of the study. References and letters in brackets match those found in Table 1
time $[6,7,13]$, while the remaining studies $(n=4)$ used a fixed-distance cycling time-trial [9].

### 3.4.2 Continuous and Fixed-Power Output Protocols

Two studies used a continuous, fixed-power output test to exhaustion, conducted at the same relative exercise intensity throughout [16, 17]. Three studies used a continuous exercise protocol where an initial fixed power output bout of exercise was followed by another one at a higher intensity [10, 14]. Two studies used a continuous exercise protocol where a first fixed-power output exercise period was followed by one where participants had to perform the greatest amount of work possible in a designated amount of time [8].

### 3.4.3 Environmental Conditions, Exercise Intensity and Exercise Duration

The mean ambient temperature, relative humidity, exercise intensity and exercise duration observed in the 15 studies combined was $22 \pm 6{ }^{\circ} \mathrm{C}, 50 \pm 12,69 \pm 12 \%$ of $\dot{\mathrm{V}}_{\text {opeak }}$ and $69 \pm 12 \mathrm{~min}$, respectively (Table 1).

### 3.5 Fluid Consumption and Hypohydration Level

Overall, the mean total fluid consumption for the 15 included studies was $1400 \pm 556 \mathrm{~mL}(16 \pm 6 \mathrm{~mL} / \mathrm{min})$, with a rate of fluid intake based on body mass of




Fig. 3 Correlations between the change in power output and the rate of fluid intake (a), exercise duration (b) and exercise intensity (c). Diameters of circles are proportional to the weight of the study. $\dot{\mathrm{V}}_{\mathrm{o}_{2 \text { peak }}}$ peak oxygen consumption
$0.23 \pm 0.08 \mathrm{~mL} / \mathrm{kg} / \mathrm{min}$. Hypohydration level for the 'no fluid intake' group reached $-2.7 \pm 1.1 \%$ of body mass, whereas the 'fluid intake' group attained $-0.8 \% \pm 1.0 \%$ of body mass. Mean rates of fluid intake and hypohydration


Fig. 4 Correlations between the change in power output and temperature (a) and humidity level (b). Diameters of circles are proportional to the weight of the study


Fig. 5 Correlations between the change in power output and rate of fluid intake, while taking into account exercise duration. Diameters of circles are proportional to the weight of the study. Open circle represents exercise duration of 1 h , dotted circle represents exercise duration $>1$ to $\leq 2 \mathrm{~h}$, dashed circle represents exercise duration $>2 \mathrm{~h}$


Fig. 6 Correlations between the prevention of body mass loss and the percentage change in power output (a) and the fluid intake-associated hypohydration level and the percentage change in power output (b), while taking into account exercise duration. Diameters of circles are proportional to the weight of the study. Open circle represents exercise duration of 1 h , dotted circle represents exercise duration $>1$ to $\leq 2 \mathrm{~h}$, dashed circle represents exercise duration $>2 \mathrm{~h}$
levels based on exercise duration classification are reported in Table 1.

### 3.6 Exercise Performance

### 3.6.1 Overall Weighted Mean Effect Summary

The impact of fluid intake on ECP is shown in Fig. 2. These data were normally distributed. Drinking fluid during exercise did not significantly improve or impair cycling performance $(1.08 \pm 0.91 \%, 95 \%$ CI -0.7 to $2.9 \%$; $p=0.23$ ), based on 15 comparisons from nine studies. Within this model, the impact of fluid intake on ECP was considered trivial. A computation using only one finding per research article yielded an effect of drinking on cycling performance of $0.9 \pm 0.9 \%$ ( $95 \%$ CI -0.9 to $2.8 \%$;
$p=0.32$ ). The magnitude of this effect was no different from that determined when all individual studies were considered to be independent $(p=0.93)$. A sensitivity analysis demonstrated that the deletion of each study one at a time from the model changed neither the magnitude nor the significance of the impact of fluid intake on ECP.

### 3.6.2 Heterogeneity

Visual examination of Fig. 2 suggested a lack of homogeneity of the effect of fluid intake on ECP, which was statistically confirmed by a $Q$ of $49.5(p<0.01)$ and an $I^{2}$ value of $72 \%$ (high heterogeneity). The widely different responses to the effect of drinking during exercise explains in part the trivial and nonsignificant change in ECP reported in Fig. 2.

### 3.6.3 Publication Bias

Inspection of the funnel plot (figure not shown) suggested no significant publication bias. Moreover, the Egger's test of the intercept $(-0.10 \pm 0.82 \%)$ was not statistically significant ( $p=0.45$ ). Fourteen unpublished studies, with a mean change in ECP of $2 \%$ due to fluid intake, would be needed before the weighted mean treatment effect would become practically significant and relevant (i.e. $>1.6 \%$ ). Based on a left trim-and-fill correction of two additional studies, the potential impact of publication bias would be to reduce the effect of drinking on ECP by $0.62 \%$, down to $0.46 \%$ ( $95 \%$ CI -1.38 to $2.30 \%$ ).

### 3.6.4 Meta-Regression Analyses

Figure 3 shows the relationships between the change in ECP and the rate of fluid intake during exercise, exercise duration and exercise intensity. There was no significant correlation between the rate of fluid intake during exercise and the change in ECP ( $p=0.73$ ); however, significant relationships were observed between the change in ECP and exercise duration ( $p=0.03$ ) and intensity ( $p=0.03$ ). Figure 4 demonstrates that there was no significant correlation between the change in power output and ambient temperature ( $p=0.10$ ) or humidity level $(p=0.78)$. The impact of drinking on ECP in studies using continuous, fixed-power output ( $0.6 \pm 1.7 \%$ ) versus time-trial $(1.5 \pm 1.3 \%)$ exercise protocols was not significantly different ( $p=0.67$ ).

There was a significant ( $p<0.01$ ) and relatively strong ( $R^{2}=64 \%$ ) correlation between exercise duration and intensity (results not shown); however, when both variables were combined in the same model, exercise intensity did not provide any additional information beyond that supplied by exercise duration. Since exercise duration


Fig. 7 Forest plots demonstrating the impact of fluid intake on cycling performance during exercises durations $1 \mathrm{~h}(\mathbf{a}),>1$ to $\leq 2 \mathrm{~h}$ (b) and $>2 \mathrm{~h}(\mathbf{c})$. CI confidence interval, filled diamond represents the
overall weighted mean treatment effect. Sizes of squares are proportional to the weight of the study. References and letters in brackets match those found in Table 1
correlated with the rate of fluid intake during exercise, we determined if the rate of fluid intake correlated with the change in power output while controlling for the effect of exercise duration. In that respect, Fig. 5 shows that there was a significant correlation between the rate of fluid intake during exercise and the change in power output for cycling duration of $>1$ to $\leq 2 \mathrm{~h}(p<0.01)$ and $>2 \mathrm{~h}(p<0.01)$, but not when exercise duration was $1 \mathrm{~h}(p=0.76)$.

As demonstrated in Fig. 6a, there was a significant positive correlation between the capacity of fluid intake to prevent the loss of body mass and change in power output
( $p<0.01$ ). Figure 6b demonstrates that this relationship was dependent on exercise duration since the hypohydration level observed in the fluid intake group was correlated with the change in power output for cycling exercise duration of $>1$ to $\leq 2 \mathrm{~h}(p<0.01)$ and $>2 \mathrm{~h}(p=0.01)$, but not when exercise duration was $1 \mathrm{~h}(p=0.58)$.

The above findings indicate that the impact of fluid intake and associated hypohydration level on ECP is exercise duration-dependent. Based on this observation, the following section reports the impact of fluid intake on ECP for exercise duration of $1 \mathrm{~h},>1$ to $\leq 2 \mathrm{~h}$ and $>2 \mathrm{~h}$.


### 3.6.5 Weighted Mean Effect Summary Based on Exercise Duration

Figure 7 reports the impact of fluid intake on ECP during exercise duration of $1 \mathrm{~h},>1$ to $\leq 2 \mathrm{~h}$ and $>2 \mathrm{~h}$. All performance outcomes were normally distributed. Whether all studies were considered independently $(-2.5 \pm 0.8 \%$, $95 \%$ CI -4.1 to $-0.1 \%$ ) or when only one study per

4Fig. 8 Rates of fluid intake associated with changes in cycling performance for exercises of $1 \mathrm{~h}(\mathbf{a}),>1$ to $\leq 2 \mathrm{~h}(\mathbf{b})$ and $>2 \mathrm{~h}(\mathbf{c})$ in duration, while taking into account the change in power output and the corresponding fluid intake-associated hypohydration level. Arrow represents the threshold for performance gain/decrement. Dashed arrow a threshold loss of body mass of $2 \%$. Filled rectangle represents the range of rate of fluid intake associated with most performance gains. Filled circle represents the change in power output. Open square represents the fluid intake-associated hypohydration level. Straight line represents the relationship between fluid intake and the change in performance. Dotted line represents the relationship between the rate of fluid intake and the fluid intakeassociated hypohydration level
research manuscript was included in the model $(-2.7 \pm 1.1 \%, 95 \% \mathrm{CI}-4.8$ to $-0.5 \%)$, drinking during exercise of 1-h duration resulted in a significant reduction of ECP. The impact of drinking during 1-h-long cycling exercise is likely important. The outcome was not different using a random-effects weighted mean effect summary. A sensitivity analysis demonstrated that the deletion of each study one at a time from the model changed neither the magnitude nor the significance of the impact of fluid intake on ECP. On the other hand, when exercise duration was $>1$ to $\leq 2 \mathrm{~h}(2.1 \pm 1.5 \%, 95 \%$ CI 1.2-2.9\%) [random-effects model: $2.0 \pm 0.8 \% ; p=0.02$ ] or $>2 \mathrm{~h}(3.2 \pm 1.2 \%, 95 \%$ CI $0.8-5.6 \%$ ) [random-effects model: $4.2 \pm 2.3 \%$; $p=0.06]$, ECP was significantly improved by drinking fluid. The impact of fluid intake on ECP under real-world conditions is likely or very likely to be important ( $>1.6 \%$ meaningful change) [2]. When dependency among studies was taken into account during cycling duration $>2 \mathrm{~h}$, drinking tended ( $p=0.052$ ) to benefit ECP and increased power output by $4.7 \pm 2.4 \%$ ( $95 \%$ CI -0.0 to $9.4 \%$ ). For exercise duration $>1$ to $\leq 2 \mathrm{~h}$, a sensitivity analysis indicated that deleting each study one at a time from the model did not substantially alter the magnitude of the effect of fluid intake on ECP. However, when the study of Maughan et al. [16] was removed from the summary, the effect became nonsignificant. For cycling exercise $>2 \mathrm{~h}$ in duration, removing the study of Dugas et al. [9] from the model doubled the effect of fluid intake on ECP. Removal of any other studies did not change the magnitude of the effect of drinking on ECP, but deleting that of Dugas et al. [9] or McConell et al. [10] removed significance.

### 3.6.6 Optimal Rates of Fluid Intake Based on Exercise Duration

3.6.6.1 Exercise of 1-h Duration Figure 8a demonstrates that, with the exception of one study [6] where fluid intake proved beneficial to ECP, fluid intake in the range of $0.15-0.34 \mathrm{~mL} / \mathrm{kg}$ body mass $/ \mathrm{min}$ either had no impact or
decreased power output, despite preventing $>2 \%$ loss of body mass. That was true for cycling exercise performed in temperate [7, 8, 13] and warm ambient conditions [7], and for continuous, fixed-power output [8] and time-trial [7, 13] exercise protocols.
3.6.6.2 Exercise $>1$ to $\leq 2 h$ Duration As depicted in Fig. 8b, it appears that fluid intake in the range of $0.15-0.20 \mathrm{~mL} / \mathrm{kg}$ body mass $/ \mathrm{min}$ has a positive and graded impact on ECP. These rates of fluid intake were sufficient to prevent $>2 \%$ loss of body mass in temperate $[16,17]$ and warm [14] ambient conditions. Although these findings were all derived from studies that used continuous, fixedpower output exercise protocols, we propose that there is no reason to believe that they could not also apply to out-of-doors cycling exercise conditions (i.e. road races/time trials). In fact, the impact of drinking on ECP was similar for both types of exercise protocols during 1 h (Fig. 8a) and $>2 \mathrm{~h}$ (Fig. 8c) cycling periods.
3.6.6.3 Exercise $>2 h$ Duration As suggested in Fig. 8c, the rate of fluid intake associated with the greatest performance improvement during cycling exercise $>2 \mathrm{~h}$ in duration conducted in temperate [10] and warm [9] ambient conditions appears to be between 0.14 and $0.27 \mathrm{~mL} / \mathrm{kg}$ body mass $/ \mathrm{min}$. These findings applied to both time-trial [9] and continuous, fixed-power output [10] exercise protocols. This model further suggests that drinking above a rate of $0.27 \mathrm{~mL} / \mathrm{kg}$ body mass $/ \mathrm{min}$ provides no additional increase in cycling performance. The results also showed that a drinking rate of $0.16 \mathrm{~mL} / \mathrm{kg}$ body mass $/ \mathrm{min}$ consumed ad libitum was linked to the greatest improvement in ECP. Figure 8c shows that drinking at a rate above the dictates of thirst sensation was sufficient to prevent $>2 \%$ loss of body mass [10], whereas a rate of drinking according to thirst sensation allowed a loss of body mass slightly greater than $2 \%$ (i.e. $2.1 \%$ body mass) [9].

## 4 Discussion

This is the first meta-analysis to (1) determine the magnitude of the effect of fluid consumption on ECP during tasks of various durations; (2) examine the relationship between rates of fluid intake and ECP; and (3) establish fluid intake recommendations based on the observations made between rates of fluid intake and ECP. The results demonstrated that (1) consuming fluid at rates between 0.15 and $0.34 \mathrm{~mL} / \mathrm{kg}$ body mass/min during 1 h of high-intensity cycling exercise is not advantageous to ECP; and (2) rates of fluid intake of $0.15-0.20 \mathrm{~mL} / \mathrm{kg}$ body mass $/ \mathrm{min}$ and ad libitum or $0.14-0.27 \mathrm{~mL} / \mathrm{kg}$ body mass $/ \mathrm{min}$ are associated with
improved ECP for exercise durations $>1$ to $\leq 2 \mathrm{~h}$ and $>2 \mathrm{~h}$, respectively. With the exception of when fluid was consumed ad libitum, these rates of fluid intake were sufficient to prevent a body mass loss $>2 \%$.

The primary aim of the current meta-analysis was to determine if fluid consumption improves ECP. The overall weighted mean effect summary indicated no benefit of fluid consumption on ECP, which was attributed to a clear heterogeneity among the included studies. Heterogeneity of results, small sample sizes and variations in the cycling task and rate of fluid intake between studies underline the complexity in formulating a practical guideline for fluid intake. Consequently, providing a set fluid prescription and volume as a blanket guideline and replacement strategy clearly does not offer a benefit to cycling performance for all individuals over a range of exercise durations, intensities and environmental conditions.

In certain situations, the rate at which fluid is consumed can be detrimental to ECP, particularly when the exercise is short and of vigorous intensity. Results of the weightedmean effect summary indicated that structured fluid intake rates ranging from 0.15 to $0.34 \mathrm{~mL} / \mathrm{kg}$ body mass $/ \mathrm{min}$ during high-intensity (approximately $80 \% \dot{\mathrm{~V}}_{\text {opeak }}$ ) cycling of 1 h reduced power output by $2.5 \%$, compared with when no fluid is ingested. In fact, in cycling tasks of 1 h , the magnitude of hypohydration was not sufficient to meaning fully perturb physiological homeostasis and power output [6-8, 13]. Interestingly, Backx et al. [22] observed that under real-world exercise conditions, trained cyclists did not consume fluid during a $40-\mathrm{km}$ time trial held in moderate ambient conditions. However, $60 \%$ of the cyclists consumed fluid (approximately $5 \mathrm{~mL} / \mathrm{kg}$ body mass) during the warm-up period and waiting time leading to the race start, which may have positively influenced ECP. It is interesting, although not surprising, to have observed that consuming large amounts of fluid during 1 h of vigorous cycling impairs performance. It has been demonstrated that above an exercise intensity of $70-75 \% \quad \dot{V}_{\mathrm{o}_{2 \text { peak }}}$, gastric emptying becomes compromised and fluid starts to accumulate in the stomach, leading to abdominal bloating, gastrointestinal discomfort and reduced cycling performance [23, 24]. In the present meta-analysis, both Robinson et al. [13] and McConell et al. [8] observed, in 16 subjects ( $50 \%$ of the total sample), that high rates of fluid consumption during vigorous 1 h cycling exercise were associated with abdominal bloating and decrements in cycling performance. Therefore, we speculate that a fluid intake rate greater than the rate of gastric emptying (or intestinal absorption) during vigorous intensity cycling of 1 h may impair performance as a result of the associated gastrointestinal distress and overall discomfort. However, fluid intake rates equal to or substantially lower than gastric
emptying, or even mouth rinsing, may have produced different results. Moreover, as demonstrated by Below et al. [25], ingesting fluid at a high rate may not be deleterious to all athletes during 1 h cycling performance.

In the present meta-analysis, the optimal rates of fluid intake for moderate-intensity cycling of durations $>1$ to $\leq 2$ $\mathrm{h}(0.15-0.20 \mathrm{~mL} / \mathrm{kg}$ body mass $/ \mathrm{min}$ ) and $>2 \mathrm{~h}$ (ad libitum or $0.14-0.27 \mathrm{~mL} / \mathrm{kg}$ body mass $/ \mathrm{min}$ ) were lower than those observed in durations of 1 h , but sufficient to limit dehydration and promote performance improvements of at least 2 and $3 \%$, respectively. Therefore, it is not clear if the effect on ECP was due to the duration and intensity of exercise or due to the intake of fluid. If fluid intake was the primary reason, it may have contributed to improving ECP through decreased cardiovascular and thermal strain [26], thirst sensation [4] or a potential placebo effect as participants were not blinded to oral rehydration [27]. Interestingly, all but one (ad libitum drinking) of these rates of fluid consumption were sufficient to maintain the loss of body mass $\leq 2 \%$, which supports the contention of Cheuvront et al. [26] that the goal of drinking during exercise is to prevent a body mass loss $>2 \%$.

As depicted in Fig. 8c, drinking fluid at a rate dictated by thirst offered the greatest performance benefit during a cycling task $>2 \mathrm{~h}$. This observation matches that of Backes and Fitzgerald [28], who recently demonstrated that ad libitum drinking improves running endurance capacity, compared with planned drinking. However, other studies have shown that ad libitum drinking does not further improve cycling [9] or running performance [29-31], compared with prescribed drinking aimed at limiting dehydration. Both drinking to thirst and planned fluid intake are viable strategies and their use should be based on the cyclist's preference, environment, course, type and duration of event, rules, and opportunities to drink. In certain situations, a cyclist may be able to plan and strategise fluid intake, while in other situations, using thirst and the opportunity to drink may be more appropriate. Based on the limited available evidence from the present meta-analysis, we cannot conclusively conclude that one strategy is superior to the other, and athletes are encouraged to adjust fluid intake in accordance with the demands of the event. Mathematical assimilation of the findings from several studies can provide additional insight, but it also has the potential to distort results if not considered in the context of the practicalities of sport performance and competition. In the event that a cyclist has not, or cannot, plan fluid intake for a given exercise task, and that drinking to thirst is not an option, the evidence-based fluid intake recommendations offered by this meta-analysis provide initial guidelines. However, this needs to take into account the possible pattern of fluid replacement during exercise, which is highly dependent on the opportunity for cyclists to
drink. Indeed, during cycling events the loss of aerodynamics, bike control, race tempo, gastrointestinal comfort or fluid collection from designated stations are considerable factors that impact when a cyclist may consume fluid. Studies are needed to examine the intricate relationship between rate of drinking, pattern of drinking and frequency of drinking on ECP.

For those studies that showed performance benefits for cycling exercises of $>1$ to $\leq 2 \mathrm{~h}$ and $>2 \mathrm{~h}$ duration, the average rate of fluid intake was 0.17 (range $0.15-0.20$ ) and 0.20 (range $0.14-0.32$ ) $\mathrm{mL} / \mathrm{kg}$ body mass $/ \mathrm{min}$, respectively. Ross et al. [32] collected data during the Tours of Gippsland and Geelong and observed that cyclists ingested fluid at a rate of approximately $0.09-0.13 \mathrm{~mL} / \mathrm{kg}$ body $\mathrm{mass} / \mathrm{min}$ during road races of, on average, $>1$ to $\leq 2 \mathrm{~h}$ in duration. This rate of fluid intake is somewhat lower than the rates at which the laboratory-based studies included in this meta-analysis provided fluid. However, it must be noted that both tours were held at ambient temperatures of approximately $15{ }^{\circ} \mathrm{C}$, which, at least in part, may explain the relatively low rate of fluid intake observed. Nevertheless, it remains to be determined whether the recommendation to drink at a rate of $0.15-0.20 \mathrm{~mL} / \mathrm{kg}$ body mass/ min during a cycling task of $>1$ to $\leq 2 \mathrm{~h}$ can be applied to real-world cycling conditions. On the other hand, studies that examined the rate of drinking of cyclists during outdoor road races $>2 \mathrm{~h}$ report rates of fluid intakes of approximately $0.09-0.30 \mathrm{~mL} / \mathrm{kg}$ body mass $/ \mathrm{min}$ [33-35], which is in line with what individuals were asked to drink in studies included in the present meta-analysis. Agreement between laboratory- and field-based observations provide evidence that the fluid intake recommendation for cycling exercise $>2 \mathrm{~h}$ can be confidently transferred to outdoor exercise conditions.

It is important that the recommendations arising from the current meta-analysis be interpreted and applied in the appropriate context. First, the influence of the rate of fluid intake on ECP is limited to nine studies, with variations in duration, intensity and rehydration strategies. Second, the incompleteness of literature related to fluid intake and cycling performance creates an inability to clearly identify the benefits of consuming realistic volumes of fluid during cycling events of 1-h duration. Third, the results of the present meta-analysis are pertinent to the reality of endurance cycling only and should not be transposed to other sports or modes of exercise. Fourth, they are relevant for competitive cyclists under racing or training conditions where peak performance is sought. Although they may potentially also apply to low-intensity training conditions, one should realise that studies from which they derive were not designed within this context. Fifth, it is unclear whether they can be extended to women since they represented only $10 \%$ of the population of subjects studied in the present
meta-analysis. Along the same line, the results of the present meta-analysis do not apply to younger ( $<18$ years) and masters ( $>50$ years) cyclists. Sixth, the present results do not apply to cyclists who commence exercise in a hypohydrated state. Finally, findings are valid for cycling conditions where ambient temperatures range from 20 to $33^{\circ} \mathrm{C}$.

## 5 Conclusions

The effect of fluid consumption on ECP is complex and needs to be considered in the context of the specific scenario in which it is applied. Based on the available literature, the results of the present meta-analysis show that consuming fluid at high rates ( $0.15-0.34 \mathrm{~mL} / \mathrm{kg}$ body mass $/ \mathrm{min}$ ) during high-intensity 1 h cycling exercise conducted between 20 and $33^{\circ} \mathrm{C}$ is not conducive to ECP. In contrast, moderate-intensity ECP may be improved under temperatures of $20-33{ }^{\circ} \mathrm{C}$ when fluid is consumed at a rate of $0.15-0.20 \mathrm{~mL} / \mathrm{kg}$ body mass $/ \mathrm{min}$ and ad libitum or between 0.14 and $0.27 \mathrm{~mL} / \mathrm{kg}$ body mass $/ \mathrm{min}$ for exercise durations of $>1$ to 2 h and $>2 \mathrm{~h}$, respectively. These fluid intake recommendations offer further options for cyclists who do not use personalised hydration plans or follow thirst as a way to gauge fluid replacement during exercise. Further work is needed to examine a more authentic view of cycling hydration during high-intensity, 1 h performance.

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