Hydration, drinking and exercise performance

Mettler S[1,2], Mannhart Ch[3]
[1] Department of Business, Health and Social Work, Bern University of applied sciences, Switzerland, samuel.mettler@bfh.ch;
[2] Department of Health Sciences and Technology, ETH Zurich, Switzerland, samuel-mettler@ethz.ch;
[3] consultingmannhart, Wolfhausen, Switzerland, mail@consultingmannhart.ch

Abstract

To counter progressive dehydration and thirst, athletes drink during exercise. However, despite decades of scientific research, there is still no conclusive answer regarding how much we should drink to optimize performance. The goal of this review article is to analyze the arguments underpinning contrasting perspectives and to critically analyze the available evidence.

It seems that the respective argumentations of contrasting viewpoints are based on a different selective fraction of the available evidence. In studies using time trial performance protocols in which dehydration develops during exercise, it seems that end-exercise dehydration levels of up to 4 % body mass do not compromise endurance performance in temperate to hot conditions – at least as long as the athlete is not prevented from drinking. In contrast, studies that induced dehydration pre-exercise consistently report performance impacts already at low levels of dehydration, i.e., 1 to 2 % body mass loss.

Further factors like the perception of thirst have been suggested to influence performance, but performance effects cannot be explained solely by the perception of thirst as well. Nevertheless, no evidence was found against the hypothesis that drinking ad libitum may optimize performance outcomes. At the same time, arguments have been identified regarding why a drinking plan might assist athletes in different situations.

Zusammenfassung

Athletinnen und Athleten trinken während dem Sport, um Flüssigkeitsdefizite und Durst zu reduzieren oder zu vermeiden. Trotz jahrzehntelanger Forschung gibt es nach wie vor unterschiedliche Sichtweisen darüber, wie viel während dem Sport getrunken werden soll, um die Leistung zu optimieren. Das Ziel dieses Reviewartikels besteht darin, die Argumente hinter sich widersprechenden Sichtweisen zu beleuchten und die verfügbare Evidenz kritisch zu hinterfragen.

Sich widersprechende Theorien scheinen auf einer unterschiedlichen selektiven Auswahl aus der verfügbaren Evidenzgrundlage zu basieren. In Studien, welche die Leistung mit Time Trials gemessen haben und sich das Flüssigkeitsdefizit während Belastung entwickelte, konnte bei milden und warmen Umgebungsbedingungen bis zu einem Flüssigkeitsdefizit von 4 % der Körpermasse kein negativer Effekt auf die Ausdauerleistungsfähigkeit festgestellt werden. Dies zumindest so lange, als die Athleten nicht am Trinken gehindert werden. Im Gegensatz dazu wurde in Studien, welche das Flüssigkeitsdefizit vor Belastungsstart induziert haben, konsistent bereits bei Flüssigkeitsdefiziten von 1 bis 2 % der Körpermasse eine Leistungsbeeinträchtigung festgestellt.

Weitere Faktoren wie die Durstwahrnehmung könnten die Leistung mit beeinflussen, wobei Leistungseffekte aber auch nicht alleine aufgrund des Durstgefühls erklärt werden können. Allerdings konnten keine Hinweise gegen die Hypothese gefunden werden, wonach gemäss Durst zu trinken die Leistung optimieren würde. Gleichzeitig gibt es auch Argumente, welche für die Ausarbeitung eines Trinkplans sprechen.

Introduction

Sweat evaporation provides an important heat dissipation avenue, particularly during high exercise intensity [1]. Prolonged sweating may result in increasing levels of dehydration, which has been associated with effects on both exercise performance and thermoregulation [1]. To counter progressive dehydration, athletes voluntarily drink as a response to their perception of thirst and because of externally applied drinking guidelines. The goal of this review article is to critically analyze the available evidence about the influence of hydration and drinking on exercise performance. Fueling effects by ingesting carbohydrates together with the fluid are not in the focus of this article.

The history of drinking

Until the late 1960s athletes were convinced that avoiding drinking during exercise would optimize performance [2]. In 1975 by the American College of Sport Medicine (ACSM) published its first drinking guidelines. Those guidelines focused on the avoidance of "heat injuries" [3]. Performance was not in the focus until the ACSM's 1996 position stand [4]. Notably, the 1996 guidelines suggested that "individuals should be encouraged to consume the maximal amount of fluids during exercise that can be tolerated without gastrointestinal discomfort up to a rate equal to that lost from sweating." Absolute drinking volumes of 0.6 to 1.2 liters per hour of exercise were recommended.

These drinking guidelines have been seriously questioned [5–8]. In addition to the criticisms of the scientific evidence for these guidelines, critics have highlighted the danger of overhydration and hyponatremia [7,9]. Indeed, at the beginning of the new millennium, overhydration and associated hyponatremia have become a mass phenomenon [10–13], indicating that the advice to drink during exercise has obviously taken root in the population around the world, but perhaps not as intended by the authors of the message. Field studies in endurance events around the world started to report a significant proportion of participants finishing the events overhydrated [11–14], with an increasing risk for asymptomatic and symptomatic hyponatremia and even fatal outcomes [13,15,16].

The 2007 ACSM position stand on exercise and fluid replacement [1] suggested ad libitum drinking from 0.4 to 0.8 liters per hour for endurance events. It was suggested to keep body mass loss <2% in order to avoid performance decrements. These arguments were confirmed in the latest ACSM position stand [17] and represent the classical perspective on the topic of dehydration, drinking and performance.

Two fundamental perspectives

Since the 1990s the classical perspective has been more and more challenged. After nearly a century of scientific research, numerous studies have been published about the influence of fluid intake and dehydration on diverse exercise performance and thermoregulatory outcomes [18–86]. Review articles and meta-analyses have tried to compile the data and to draw practical conclusions, but actually ended up with conflicting interpretations [87–96] and the scientific community is far from a common position. Instead, two fundamentally different viewpoints *(see Tab. 1)* have emerged, which have not significantly changed over the last decade [87–89].

The classical perspective

The classical view, as represented by both the 2007 [1] and 2016 [16] ACSM position stand and additional review articles about the influence of drinking or dehydration on thermoregulation and performance [86,87,93–95] adopt the following fundamental line of arguments:

1. Fluid deficits of more than 1–2% body mass impair exercise performance, in particular endurance exercise and under warm conditions.
2. Fluid deficits increase body core temperatures and thereby increase cardiovascular stress, which may impair performance and increase the risk for heat illness or heat stroke.
3. Drinking "ad libitum" or "to thirst" is not sufficient to prevent heat illness or performance decrements.

The contrasting perspective

The contrasting view challenges the classical view and provides the following line of arguments [2,6,7,13,86,88–90,92]:

1. Fluid deficits of more than 2% body mass do not necessarily impair exercise performance.
2. There is no evidence that drinking more than ad libitum or to thirst provides any performance advantage over paced fluid ingestion to minimize body mass loss to 1–2%.
3. Exercise intensity, not dehydration, is the primary cause for heat stroke.

Table 1: Two perspectives on the effect of drinking and dehydration on exercise performance and thermoregulation.

Evidence for real-life endurance performance

To allow for transferring conclusions from laboratory-based research to real-life settings, the study design should simulate real life as much as possible (i.e., the external or ecologic validity of the study). One difference between many laboratory studies and real-life settings is that the majority of studies [20–23,27–31,33,35,38–40,42–45,47–54,56–58,61,62, 66,67,69–71,73,77,82,84,86] induced dehydration before exercise, either by exercising the subject in the heat, imposing fluid restrictions of about one to two days, or administering diuretic drugs before the exercise task. This is in contrast to real life, where athletes dehydrate during exercise (exercise-induced dehydration). Further, in real life, athletes have to perform as fast as possible over a given distance while being able to self-pace their race and allow continual behavioral adjustments. In contrast, many laboratory studies used fixed-power output tests to exhaustion, which only allow an all-or-none response (exercise continuation or termination). There is no real-world sport where athletes need to perform as long as possible without being able to adjust power output and without knowing the distance or time (workload) to be covered. The ecologic validity of time to exhaustion tests, particularly combined with pre-exercise dehydration, is therefore considered as low [90,93,97].

When screening the literature for studies using time trial performance and exercise-induced dehydration, not many studies remain [19,37,60,63–65,75,76,79–81,83]. Interestingly, these studies reported no performance impact of dehydration with body mass losses up to 2% [76,79,81,83], beyond 2% [37,63,65,80], and up to 3.2% [41,60,75] or 4% [64], covering temperate to hot conditions. Exceptions are Below et al.'s [19] and Dugas et al.'s [80] studies, where drinking nothing or below ad libitum was associated with reduced performance.

Taken together, these results suggest that under lab conditions that consider two important real-life settings, end-exercise dehydration levels of up to 4% body mass do not seem to compromise endurance performance in temperate to hot conditions, at least as long as drinking is not withheld from the athlete. Two recent meta-analyses come to a similar conclusion, suggesting that studies with ecologically valid study designs do not show performance impacts of exercise-induced dehydration of up to 4% body mass [90,91], whereas studies using protocols with fixed exercise intensity and/or pre-exercise induced dehydration, 1–2% body mass loss is already associated with reduced performance [39,40,91].

Observational field data of elite endurance athletes winning international marathons have reported dehydration levels of 6.6% to 11.7% body mass [98]. Although these observations do not allow for a causative conclusion that dehydration does not influence performance, it is nevertheless a striking contrast to the classical viewpoint, which suggests that endurance performance would be impaired if dehydration exceeds 1–2% body mass loss [1].

In the 2007 ACSM position stand [1], three reviews [95,99,100] were cited for the conclusion that dehydration of >2% body mass degrades aerobic exercise performance in warm environments. The cited reviews themselves refer to further reviews and studies based on ecologically invalid study designs (e.g. time to exhaustion tests and or induction of dehydration by artificial pre-exercise protocols).

One interpretation of the conflicting viewpoints *(Tab. 1)* is that they are simply founded on different study types and a different body of evidence, which separate themselves by their ecologic validity.

Dehydration, thirst and performance

Dugas et al. [80] showed that two hour cycling time trial performance is optimized when drinking ad libitum or more during exercise, compared with restricted fluid (no fluid or less than ad libitum). Noakes [7,8] has suggested that the optimal amount of drinking is ad libitum or to thirst. In contrast, Backx et al. [81] found no effect of drinking more or less than ad libitum during a one hour cycling time trial. Daries et al. [75] or Dion et al. [60] found no positive performance effect on a two hour cycling time trial [75] or 21 km running [60] when ad libitum drinking of about 0.4 l/h was forced to 0.9 l/h or 1.3 l/h, respectively, in order to reduce end-exercise dehydration. Nevertheless, all three studies are in line with the observation that no single intervention study has ever been published showing that drinking more than ad libitum or to thirst would be associated with any performance benefits, irrespective of the end-exercise dehydration level. On the other hand, drinking less than ad libitum may [19,80] or may not [63,76,79,81,83] negatively affect performance in ecologically valid studies.

Interestingly, the perception of thirst may be reduced with increased drinking, but without affecting performance [60,64]. Simultaneously, increasing abdominal discomfort may occur [60]. This implies that maximal reduction of thirst is not the chosen level of the thirst signal when drinking ad libitum. However, it may represent the optimal drinking level from an integrated perspective of different body signals.

Fallowfield et al. [24] let subjects run to exhaustion at 70% VO_2max either by drinking nothing or by drinking a moderate amount (0.5 l/h) of water. With drinking, subjects ran 34% longer (103 vs. 77 min). Due to the longer running time, the resulting end-exercise dehydration was increased compared to the non-drinking trial. This time to exhaustion study supports the hypothesis that the dehydration level is an inferior parameter compared to ingesting fluids. Unfortunately, thirst was not assessed in this study.

In conclusion, it seems that neither dehydration nor thirst can explain performance effects on their own in laboratory-based intervention studies. Further studies with exercise durations of at least 2 h and ecologically valid study designs are needed to further understand the interaction of these parameters.

Challenges of drinking ad libitum in the field

From a laboratory-based perspective, drinking ad libitum seems to be an optimal drinking strategy. However, it has been questioned whether performance is optimized just by drinking ad libitum in all sports and in all individual real-life situations, as e.g., game rules or tactical constraints may restrict drinking to certain time points [101]. An alternative interpretation is that the definition of the term "ad libitum" is broadened by the fact that both internal body signals and external constraints are integrated to an optimal behavior.

In contrast to the two fundamental viewpoints *(Tab. 1)*, we do not see an irreconcilable incompatibility between drinking ad libitum and establishing an individualized drinking plan. Rather, without a plan we see some critical points that may arise in real life compared to laboratory-based endurance tests. We could also imagine that some of these points may interfere with the brain's ability to optimally integrate all signals, including thirst sensation, into a suitable drinking behavior. Finally, ad libitum drinking is not completely random and may become reasonably predictable after acquiring data about the athletes' drinking and body mass (see e.g. drinking calculator on http://www.ssns.ch/sportsnutrition/trinkmengenrechner). Transferring this experience into a plan may allow for planning and organization, avoiding distraction from drinking, ensuring optimal fueling, and providing guidance to athletes who are nervous or inexperienced with the exercise task to come. At the available time points, drinking may still be ad libitum. There are also real-life situations in which there may be significant arguments to drink beyond ad libitum. I.e., in tournament or multiple training situation quick recovery is easier when avoiding exaggerated dehydration, which might not be a performance problem for a single exercise task.

Tolerable upper drinking levels

Gastric emptying rates depend on, e.g., gastric filling [102], the carbohydrate content of the drink [103], and solute osmolality [104]. With repeated drinking, probably around 1.2 l/h may pass the stomach with an acceptable stomach filling during moderate intensive exercise [104].

Laboratory based studies reported gastrointestinal problems or feelings of fullness for drinking 0.9 l/h [75,81] or more [37,60,105] during running or cycling time-trials. Reported ad libitum fluid intake in laboratory based studies was between 0.4 and 0.7 l/h for one to two hours high intensity endurance running, cycling or soccer [60,63,75,80,81]. This corresponds with field observations reporting fluid intakes from 0.2 l/h to 0.8 l/h for various exercise [101]. Compared to running, higher fluid intake rates of around 1.0 l/h are occasionally observed on the bike [101], and triathletes drink more during the bike stage than during running [106]. With frequent drinking during regular recovery breaks intermittent sports seem to allow fluid intake rates of beyond 1 l/h (e.g., tennis or basketball) [101,107].

Dehydration and performance in non-endurance sports

Pre-exercise induced dehydration of ≥2% body mass resulted in consistent reports of reduced basketball skill performance and sprint times [49,51], riding [62] or golf-specific motor and mental performance [66]. Studies about basketball- and soccer-specific exercise tasks and skills while applying during-exercise dehydration are less consistent [46,55,63,74,85], with some finding no effect on the Loughborough intermittent shuttle running test (LIST) [63,85], while others reported negative effects of drinking nothing and concomitant increased dehydration on goals shot and anaerobic or sprint performance [46,55]. The difficulty of interpreting these studies is that they compared drinking nothing at all versus drinking mostly equivalent to 100% of the sweat losses. Therefore, the only practical conclusion is that drinking nothing is probably not ideal. The only study testing ad libitum drinking vs. nothing vs. equivalent to sweat losses found no difference on LIST performance for any drinking schedule [63].

A comprehensive meta-analysis of the influence of dehydration on muscle endurance, strength, anaerobic performance, and jump performance reported negative effects of dehydration of >2% body mass on muscle endurance, strength, and anaerobic performance [92], with some earlier reviews coming to similar conclusions [52,108]. In contrast, vertical jump ability was non-significantly improved with an average dehydration of 2.7 % body mass [92]. Regarding anaerobic sprint performance, it is worth noting that single sprints [45,47,48] seem to be rather unaffected by dehydration compared to repeated sprints or intermittent exercise tasks [44,50,54,68].

However, the ecologic validity of all studies mentioned above or included in Savoie et al.'s [92] meta-analysis may be questioned, as dehydration was induced by pre-exercise dehydration protocols involving heat exposure with or without endurance exercise tasks or fluid restriction of up to three days.

During-exercise dehydration is more difficult to induce in short, explosive exercise tasks compared to endurance exercise. Nevertheless, real-life competition settings may still last several hours, including preparation, sport-specific warm-up procedures, and competition with, e.g., six attempts in long jump. During these procedures, significant dehydration may undoubtedly occur and pronounced dehydration levels may be seen especially in combined events (personal observations). Regrettably, if a real-life athlete, e.g., a long jumper, would like to know whether dehydration influences his performance, we probably have to conclude that after decades of modern research, the available evidence does not allow for a conclusive answer.

Conclusion and practical implications

Based on the currently available evidence, one can conclude that drinking ad libitum is the best general advice to give to athletes. Absolute drinking volumes are difficult to recommend, although typical drinking volumes are often in the range of 0.4 to 0.8 l/h. Nevertheless, ad libitum or required drinking volumes may be below or beyond this range in some situations, and in contrast to ACSM's line of arguments, substantial evidence has emerged that exercise performance is not necessarily compromised when reaching dehydration levels of beyond 2% body mass. Further, drinking ad libitum and establishing an individualized drinking plan are compatible. Indeed, ad libitum drinking may be optimized with a drinking plan in real-life and there are situations where drinking beyond ad libitum might be advisable.

Corresponding author

Samuel Mettler
Department of Business, Health and Social Work
Bern University of applied sciences
E-Mail: samuel.mettler@bfh.ch

Department of Health Sciences and Technology
ETH Zurich
E-Mail: samuel-mettler@ethz.ch

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