Review

Hydration and Physical Performance

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There is a rich scientific literature regarding hydration status and physical function that began in the late 1800s, although the relationship was likely apparent centuries before that. A decrease in body water from normal levels (often referred to as dehydration or hypohydration) provokes changes in cardiovascular, thermoregulatory, metabolic, and central nervous function that become increasingly greater as dehydration worsens. Similarly, performance impairment often reported with modest dehydration (e.g., −2% body mass) is also exacerbated by greater fluid loss. Dehydration during physical activity in the heat provokes greater performance decrements than similar activity in cooler conditions, a difference thought to be due, at least in part, to greater cardiovascular and thermoregulatory strain associated with heat exposure. There is little doubt that performance during prolonged, continuous exercise in the heat is impaired by levels of dehydration ≥ −2% body mass, and there is some evidence that lower levels of dehydration can also impair performance even during relatively short-duration, intermittent exercise. Although additional research is needed to more fully understand low-level dehydration's effects on physical performance, one can generalize that when performance is at stake, it is better to be well-hydrated than dehydrated. This generalization holds true in the occupational, military, and sports settings.

Key teaching points:

- Dehydration during physical activity is commonplace because voluntary fluid intake is often less than fluid loss through sweating.
- Dehydration results in unavoidable, negative effects on physiological function and exercise performance. The magnitude of the effects of dehydration is exacerbated by increases in heat stress, exercise duration, and exercise intensity.
- Adequate drinking during exercise helps attenuate the reductions in blood volume, cardiac output, muscle blood flow, skin blood flow, the rise in core temperature, and the impairment in exercise performance that accompany dehydration.

INTRODUCTION

A number of consensus papers from scientific organizations [1–3] and numerous review articles [4–6] have comprehensively summarized dehydration's impact (a decrease in body fluid from the normal-euhydrated-state) on physical performance, with the consistent conclusion that dehydration can significantly impair performance, particularly during sustained physical activity in warm/hot conditions. For that reason, fluid-replacement guidelines [e.g., 1,3,7] have been established for athletes, soldiers, and workers to help encourage sufficient fluid intake to minimize the extent of dehydration during physical activity.

The purpose of this review article is to first summarize how dehydration affects physical performance. That summary will serve as a prelude to consideration of the extent of dehydration required to impair performance. The current scientific consensus is that dehydration equal to or exceeding a loss of 2% of euhydrated body mass (e.g., a loss of 1.4 kg in a 70-kg athlete; 3 lb in a 150-lb athlete) can negatively impact physical performance. In fact, it is not uncommon for athletes, soldiers, and workers to finish exercise dehydrated by considerably more than −2% of body mass, even when fluid is freely available [8]. There are two primary reasons for this "voluntary" dehydration: 1) sweat loss during physical activity can be quite large, ranging from as little at 400 ml/h to well over 2 L/h [9],

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and 2) the voluntary desire to ingest fluid during physical activity often fails to keep pace with the rate at which sweat is lost [10,11]. Regardless of the reasons for dehydration, the existing scientific data allow for this generalization: during physical activity, it is better to be well-hydrated than to be dehydrated [12,13]. Just how close to euhydrated one must remain to avoid a performance decrement remains a matter of continuing scientific interest and is the focus of the latter part of this paper.

SWEAT AND SODIUM LOSS DURING PHYSICAL ACTIVITY

There is substantial variation in the sweating rates among individuals, even under like conditions of environment, exercise intensity, fitness level, and the extent of heat acclimation [3–5]. Similarly, the rate of sweating, and therefore the total amount of sweat lost, differs markedly from day to day in the same individual, owing largely to differences in environment, exercise intensity, exercise duration, and the type of clothing and equipment worn. Because sweat loss and fluid intake during physical activity vary so widely, some individuals will encounter significant dehydration, while others will finish the same activity with minimal dehydration.

Water Loss during Physical Activity

During light exercise in cool or moderate environments, sweating rates might be as little as 100 ml/h (3 oz), yet during vigorous exercise in a hot environment, some individuals are capable of sweating at over 3,000 ml/h (roughly 100 oz) [9]. High sweating rates (e.g., $>$ 1.5 L/h) makes significant dehydration and impaired performance more likely because even highly motivated individuals find it difficult to drink large volumes during exercise and because maximal gastric emptying rate has an upper limit. This limit has yet to be well defined, is likely to vary widely among individuals, but could be in excess of 1.3 L/h [5]. Because of the substantial differences in sweating rates among individuals, there is no one-size-fits-all recommendation for fluid intake during physical activity. Remaining well-hydrated requires athletes, soldiers, and workers to continually adjust their fluid intake patterns to reflect the extent of sweat loss during exercise and thereby minimize dehydration.

Salt Loss during Physical Activity

During prolonged physical activity, large amounts of salt (sodium chloride) can be lost in sweat [8,14]. On average, human sweat contains 40–50 mmol of sodium per liter (920 to 1,150 mg/L.) Large sweat losses promote large salt losses; for example, an athlete with an average sweat sodium concentration who loses 5 L of sweat in a day, will lose between 4,600 and 5,750 mg of sodium (the equivalent of 11.5 to 14.4 g of salt.) Individuals with higher fluid losses and/or saltier sweat can lose substantially more sodium on a daily basis. It should be noted that athletes, workers, and soldiers who are fit and acclimated to the heat typically benefit from enhanced sodium reabsorption in the sweat-gland tubule, an adaptive response that helps protect plasma volume by lowering sodium loss. In fact, some individuals are capable of producing sweat with less than 20 mmol of sodium per liter [12,14]. Salt loss in itself does not have a direct impact on physical performance, but adequate replacement of sodium chloride during physical activity can help encourage voluntary fluid intake [15], protect plasma volume [16], and reduce urine production [17]—all responses that promote hydration.

IMPACT OF HYDRATION STATUS ON PHYSIOLOGICAL FUNCTION AND EXERCISE PERFORMANCE

For experimental purposes, dehydration can be induced by fluid restriction before or during exercise, heat exposure before exercise, or diuretic use before exercise. In general, studies assessing physiological and performance responses typically used dehydration levels of -2% body mass or more to produce enough fluid loss to ensure measurable changes and because such levels of dehydration are common among athletes, soldiers, and workers [6,8]. Sweating during physical activity can quickly result in dehydration, particularly in profuse sweaters in warm environments. Depending upon the adequacy of fluid intake, dehydration of 1 to 8% of body mass can occur during physical activity [5,8].

Dehydration and Physiological Function

Dehydration's impact on a variety of cardiovascular and thermoregulatory functions is measurable early in exercise (e.g., within 30 min) at a body mass loss of approximately 1%; as the level of dehydration increases, deterioration in physiological function progressively rises [3,13,18]. For example, progressive dehydration to -4.9% of body mass during two hours of cycling in the heat (65% VO_2max; 35°C; 95°F) caused heart rate, core temperature, and perceived exertion ratings to continually increase over time, while blood volume, stroke volume, cardiac output, and skin blood flow all decreased [18]. Similar results were reported by Montain and Coyle who demonstrated that levels of dehydration of -1%, -2%, -3%, and -4% of body mass were increasingly detrimental to cardiovascular and thermoregulatory function [13].

These and other data led Cheuvront et al. [19] to propose that dehydration induces premature fatigue during sustained exercise by increasing thermoregulatory stress, cardiovascular strain, negative changes in muscle metabolism (e.g., accelerated rate of glycogen depletion), and alterations in central nervous system function (e.g., reduced motivation and effort).

In short, dehydration negatively affects a wide range of physiological functions, the combined effect of which is impaired performance. Cheuvront et al. [19] point out that for many physically active people, a fluid intake of approximately 1 L/h will usually provide sufficient water, carbohydrate, and electrolytes to limit dehydration to less than −2% body mass and supply enough exogenous carbohydrate to provide an additional performance benefit [16]. Fortuitously, an intake approximating 1 L/h is very manageable for most adults [15] whose gastric emptying rates exceed 1 L/h.

Not surprisingly, dehydration's impact on physiological function is greater in warm environments than in cold [4,20,21]. When even modest heat stress (e.g., > °16C; 60°F) is present, cardiovascular strain rises and makes maintaining blood volume more critical to sustain blood flow to active muscles, skin, and the brain [21].

Dehydration and Performance

A variety of performance tasks have been studied in hydration-related experiments, including measurements of time to exhaustion, time-trial type protocols, sprint-to-the-finish protocols, and designs employing tests of sports-specific skills, muscular strength, muscular endurance, and anaerobic performance. Three studies spanning 1944 to 2007 are summarized below. The experimental designs and performance tasks used in these studies are markedly different, but the uniformity of the results reflects the current consensus of scientific literature: dehydration incurred before or during sustained exercise often impairs physical performance. Although research on dehydration's effect on muscle strength and anaerobic performance is equivocal and more work is needed, the current scientific consensus is that dehydration has little impact on such measures [3].

In 1944, Pitts et al. [11] published a study designed to determine how water, salt, and glucose intake affected physical performance in the heat. Six heat-acclimated male subjects completed a series of walks at 3.5 mph (2.2 km/h) in either hot/dry (100°F; 38°C with 30%RH) or hot/humid environments (95°F; 35°C with 83%RH). The walks lasted between one and six hours, with a 10-min rest following each hour. The authors detail the results of one subject who completed six treadmill walks (at a 2.5% grade), all in hot/dry conditions. On two occasions, the subject drank nothing. During another two trials, the subject drank according to thirst. Dehydration was prevented in the other two trials by having the subject drink water every 15 minutes in volumes that equaled his sweat loss. Based on measurements of rectal temperature, heart rate, sweating rate, oxygen consumption, and exercise duration, Pitts et al. observed:

> "First, without water the rectal temperature rose steadily to high levels and showed no signs of reaching a steady state. Although the subject, being of far better than average stamina, was able to march sixteen miles, he was very tired and inefficient at the end. Second, without water for the first hour, but thereafter enough to keep thirst quenched at all times, the rectal temperature finally started to rise after remaining constantly low for thirteen miles. The subject was able to finish nineteen miles in fairly fresh condition. Finally, when he forced himself to drink water at the same rate as he lost sweat, the body temperature remained very low for this type of work, and the subject after sixteen miles said that he could easily go on all day."

It is not apparent from Pitts et al. [11] if steps were taken to standardize the pre-exercise hydration status of their subjects. The authors did not report changes in their subjects' body mass from which percent dehydration could be calculated. However, it is clear from their data that the best physiological and performance responses occurred when dehydration was kept to a minimum.

The effect of modest dehydration incurred during relatively short-duration exercise was studied by Below et al. [16]. Their research design consisted of 50 min of cycling at 85% VO_2max, followed by a performance task requiring subjects to complete a set amount of work as fast as possible (requiring ~10 to 12 min). The protocol was designed to mimic the demands of a sprint to the finish at the end of a 40 km cycling time trial. The experiment consisted of four counterbalanced trials conducted in a warm environment (31°C; 88°F), including a trial in which about 80% of sweat loss was replaced (average water intake of 1.33 L) and a trial in which the subjects ingested an average of 200 ml of water during the exercise, enough to replace 13% of sweat loss. The researchers standardized pre-exercise hydration status by requiring subjects to consume a standard diet and refrain from exercise the day before each trial. In the 2 h prior to exercise, the subjects ingested 5 ml of water per kilogram of body mass. As a result, there were no differences in pre-exercise measures of body mass or hemoglobin concentration.

When the subjects ingested the small volume of water, they dehydrated by −2% of body mass and their performance was impaired by an average of 6.5% compared to the trial in which they replaced 80% of sweat loss. The authors noted that better hydration during exercise was associated with lower esophageal temperature, heart rate, and ratings of perceived exertion, all factors that could have influenced the subjects' self-selected work rates during the performance task.

In 2007, Ebert et al. [22] published a study designed to determine if the body mass loss associated with dehydration would actually benefit performance in uphill cycling by "lightening the load," thereby reducing the energy cost of cycling or increasing the power-to-mass ratio, either of which would result in better cycling performance. Following preliminary testing and familiarization sessions, eight trained cyclists participated in two experimental trials: low fluid intake or high fluid intake. Each trial consisted of 2 h of steady-state cycling at 53% of each subject's predetermined maximal aerobic power output, followed by a cycling bout to exhaustion. The steady-exercise took place on a cycle ergometer. After 2 h of exercise, the subjects were reweighed within 3 min and thereafter mounted their own bicycles and began to cycle on a treadmill set at an 8% grade and a speed approximating 88% of each subject's maximal aerobic power output. Time to voluntary exhaustion was recorded as the performance measure.

Euhydration prior to each trial was ensured by having the subjects ingest a standard diet for the preceding 24 h, restricting exercise and caffeine intake before each trial, and having the subjects ingest an average of 350 ml of water during the 2 h before testing. Subsequent measures of body mass, urine specific gravity, hemoglobin, and hematocrit did not differ between trials, indicating that the subjects began each trial similarly hydrated. Both trials were conducted in a warm environment (29.3°C; 85°F). During the 2-h submaximal exercise, the subjects ingested either a small volume (total = 0.4 L) or a larger volume (total = 2.4 L) of a carbohydrate-electrolyte beverage; each volume was divided into either 50 ml or 300 ml aliquots ingested at 15-min intervals. Carbohydrate intake was standardized by having subjects ingest carbohydrate gels at regular intervals during the submaximal exercise bout in the low-fluid trial. The fluid-intake regimens were purposefully designed to reflect common practices among many competitive cyclists (low intake) and the upper level of fluid intake based on previous American College of Sports Medicine recommendations [23].

At the end of the 2-h submaximal exercise bout, the subjects had dehydrated by an average of −2.5% of starting body mass on the low-fluid-intake trial; dehydration was prevented by the high-fluid-intake regimen (average +0.3% change in body mass.) Following the performance task, the subjects had dehydrated by an average of −3.6% body mass on the low-intake trial and −1.3% body mass on the high-intake trial.

Every subject performed worse on the low-intake trial. Average time to exhaustion was 5.6 min slower, a relative performance impairment of 28.6%. The authors concluded that, ". . . dehydration-induced hyperthermia outweighed the theoretical benefit of a reduction in body mass on the power-to-mass ratio and energy cost during cycling."

Under many circumstances, dehydration impairs physical performance, but it should be noted that may not always be the case. A few studies have reported no performance impairment at dehydration levels of −2% to −3% body mass [24–27]. However, new research continues to illustrate the detrimental effect that modest dehydration can have on various types of performance tasks. For example, Dougherty et al. [28] reported significant impairment in basketball skill performance at dehydration of −2% body mass in adolescent subjects exercising in a temperate environment. Future research is needed to help further our understanding of the complex relationship among hydration status, exercise intensity, exercise duration, exercise task, and thermal stress, the combined effects of which determine whether modest dehydration will negatively impact performance.

Hydration Status in Cold Environments

Although the majority of scientific evidence illustrates that dehydration impairs physical performance, there are circumstances in which modest dehydration (e.g., −2% to −3% body mass) does not significantly alter performance. One of those circumstances is exercise in cold weather. Cheuvront et al. [21] showed that dehydration (−3% body mass) impaired exercise performance in a temperate environment (20°C; 68°F), but not in a cold environment (2°C; 36°F). The performance task consisted of 30 min of steady-state cycling at 50% VO_2peak, followed by 30 min in which the subjects (n = 8) attempted to complete as much work as possible. The authors reasoned that higher cardiac output and lower core temperature during exercise in the cold may explain why dehydration has less of an effect on performance. However, additional research needs to be accomplished to confirm these suspicions, in part because other investigators have reported performance impairment associated with dehydration in cold environments [29].

Hyperhydration and Performance

Hyperhydration refers to an increase in body fluid above the euhydrated state. This can be achieved by ingesting excess water, often combined with a molecule such as glycerol to create an osmotic imperative for temporary water retention. Within a few hours, the excess fluid is excreted as urine, but within that timeframe, hyperhydration could have performance advantages by delaying dehydration and blunting the rise in core temperature. A few studies reported small performance improvements associated with hyperhydration [30–32]. However, the current prevailing scientific consensus is that hyperhydration does not provide a meaningful physiological or performance advantage compared to remaining well-hydrated during exercise [3,33–36].

Hydration Status and Performance in the Occupational Setting

In addition to the sports setting, there are numerous other occasions when hydration can be a critical determinant of physical performance. Jobs in mining, agriculture, logging, firefighting, and construction often expose workers to hot environments and steady physical work that may require protective clothing and job-related equipment. Similar conditions hold true for soldiers, from basic training to some day-to-day duties and wartime.

Research demonstrates that, as in the athletic setting, protecting hydration status improves performance in the occupational setting [3]. Dehydration has been shown to reduce physical work capacity and lower heat tolerance, particularly in settings of uncompensable heat stress (i.e., environments that do not allow sufficient heat loss to enable core temperature to plateau at safe levels). When hydration status is protected by adequate fluid intake during physical activity, heat tolerance and performance are improved. [37–39].

HOW MUCH FLUID LOSS IS REQUIRED TO IMPAIR PERFORMANCE?

Current practical guidelines identify a loss of 2% of body mass as the level of dehydration at which performance impairment is likely to occur. This guidance is reflected in a 2005 scientific consensus statement issued by the American College of Sports Medicine: "Dehydration of more than 2% of body mass can compromise physiological function and impair exercise performance capacity. Greater levels of dehydration further exacerbate the negative responses" [2]. There is ample scientific evidence to corroborate that performance impairment often occurs when 2% or more of body mass is lost before or during exercise. However, it is unlikely that a loss of 2% of body mass represents a set physiological threshold above which performance is compromised. There may be exercise and environmental conditions where less than a 2% loss in body mass results in a performance decrement. In fact, a handful of studies suggest this may indeed be the case. Although considerably more research is needed to confidently conclude that slight dehydration may impair performance, results of the following studies suggest such a possibility.

One of the most frequently cited studies that illustrates performance decrement associated with dehydration is that of Armstrong et al. [40] This group studied eight experienced runners who were required to complete runs of 1.5 km, 5.0 km, and 10.0 km on an outdoor, 400 m track in cool conditions (15.7°C; 60°F.) The authors relied on measuring plasma sodium and potassium concentrations to verify similar hydration status among the subjects prior to the diuretic and control trials. A unique aspect of this study is that dehydration was accomplished by ingesting 40 mg of furosemide diuretic 5 h before exercise. The experimental protocol was intended to reduce the subjects' plasma volumes by 2%. This led to reductions in body mass of 1.9% (1.5 km), 1.6% (5.0 km), and 2.1% (10.0 km). Compared to runs in the euhydrated state, dehydration increased run times by 3.1% (1.5 km), 6.7% (5.0 km), 6.3% (10 km); dehydration significantly increased the time required to complete the 5- and 10-km runs. From these results, the authors recognized that a small amount of dehydration could negatively impact performance: "Linear regression analysis indicated that a 1% change in body mass corresponded to running time increases of +0.17, +0.39, and + 1.57 min, respectively for the 1,500 m, 5,000 m, and 10,000 m trials."

Walsh et al. [41] reported that dehydration of −1.8% of body mass significantly impaired performance following 60 min of cycling exercise at 70% VO_2peak. Subjects (n = 6) exercised in the heat (32°C; 90°F) on two occasions, one where they did not ingest any fluid and the other where they drank 400 ml of a dilute saline solution (20 mmol/L) 2 to 3 min before exercise and 120 ml every 10 min for the first 50 min of exercise. There were no differences in plasma osmolality or body mass prior to the trials, indicating that the subjects were similarly hydrated for each trial. The performance task required the subjects to cycle to exhaustion at 90%VO_2peak. When the subjects remained well-hydrated, they exercised for an average of 9.8 min, about 3 min longer than when dehydrated, and performance improved by 44%. These results further demonstrate the performance-related importance of staying well-hydrated during exercise in the heat, even during relatively short-duration exercise, and also provide a directional indication that low levels of dehydration (i.e., $< -2\%$) can impair performance.

Maxwell et al. [42] reported that low-level dehydration impaired performing a high-intensity, short-duration running task conducted in a temperate environment. The investigators used a maximal intermittent running test to measure performance. Subjects (n = 11) were required to complete repeated 20-second treadmill runs of increasing intensity at a 10.5% grade, interspersed with 100 seconds of standing rest. The tests were conducted in a cool environment (21°C; 70°F) and performance was determined by the cumulative time of the high-intensity runs. Pre-exercise hydration was standardized by having the subjects consume 500 ml of water 90 min before arriving at the lab; pre-exercise urine-specific gravity and body mass measures did not differ between trials. Subjects undertook approximately an hour of passive and active heat stress that included 10 min in a hot bath, followed by intermittent walking and jogging until dehydration had reached −1.5% body mass. This was followed by 2 h of recovery in ambient laboratory conditions. For the euhydration trial, subjects ingested a sugar-free, lemon-flavored saline solution (80 mmol/L) while walking/jogging and during the first 40 min of the 2-h recovery period. The total volume ingested was 155% of predicted sweat loss to account for obligatory urine excretion during the recovery session. Sweat loss during the performance test averaged 500 ml for both trials, resulting in final dehydration values of −2.0% and −0.6% body mass for the dehydrated and euhydrated trials, respectively. The −2% level of dehydration significantly impaired running performance by about 4% (148 ± 9 s vs. 154 ± 9 s). Heart rate and rectal temperature were both significantly elevated during the dehydration trial, indicating greater cardiovascular and thermoregulatory strain.

The data of Armstrong et al., Walsh et al., and Maxwell et al. [40–42] show performance decrements at low levels of dehydration and lend credence to the generalization that when performance is at stake, it is better to be well-hydrated than dehydrated. However, additional research is required to further investigate the effects of low-level dehydration on physiological and performance responses in cold, temperate, and hot environments. Determining how low-level dehydration might affect performance in short- and long-duration steady-state and intermittent exercise tasks will require additional measures of cardiovascular and thermoregulatory function, muscle temperature, muscle/blood metabolites, perceived exertion, and other parameters. It is also important from both a practical and scientific perspective to further characterize the types of performance tasks (e.g., aerobic, anaerobic, strength, sports-specific, etc.) that are sensitive to changes in hydration status.

SUMMARY AND CONCLUSIONS

The results of many decades of research make it clear that dehydration often impairs physical performance. For that reason, current practical guidelines [3] encourage consumption of sufficient fluid volumes during exercise to minimize dehydration. This can often be accomplished by ingesting about 1 L of fluid per h (or whatever level approximates but does not exceed sweat loss). Under circumstances where significant dehydration cannot be avoided (e.g., in the case of profuse sweaters or when fluid availability is limited), the goal should be to take steps to reduce dehydration severity by ingesting as much fluid as comfortably tolerated (without over-drinking) and by taking advantage of any opportunity to reduce sweating rate (e.g., minimizing the intensity of warm-up exercise, removing clothing and equipment, taking more frequent rest breaks, decreasing exercise intensity, and taking advantage of the increased convective heat loss associated with breezes and the increased radiative heat loss experienced in the shade).

In summary, drinking sufficient volumes of fluid during physical activity to minimize dehydration is arguably the simplest and most effective means of sustaining physiological function and improving physical performance.

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