

The Importance of Good Hydration for Work and Exercise Performance

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This review covers published literature on the influence of whole-body hydration status on exercise performance. The majority of information in this area relates to endurance exercise performance, but information on power, strength, and sporting skills has also been investigated. These areas form the focus of the current review. It is apparent that some individuals can tolerate body water losses amounting to 2% of body mass without significant risk to physical well-being or endurance exercise performance when the environment is cold (for example 5°C–10°C) or temperate (for example 20°C–22°C). However, when exercising in a hot environment (an environmental temperature of 30°C or more), dehydration by 2% of body mass impairs exercise performance and increases the possibility of suffering a heat injury.

Key words: dehydration, exercise performance, body water balance

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INTRODUCTION

Hydration status, water consumption, and the effects of hypohydration on exercise performance, work performance, health, and well-being have been the topic of much public and scientific debate in recent years. The effect of body water balance on aspects of exercise performance has been extensively researched and, in recent years, reviewed comprehensively.^{1–3} The majority of research in this area has been undertaken with regard to endurance exercise performance, but the effects on power, strength, and skills have also been investigated. These areas form the focus of the current review.

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The balance between the loss and gain of fluids maintains the body water within relatively narrow limits.⁴ The routes of water loss from the body are the urinary system, the skin, the gastrointestinal tract, and the respiratory surfaces. The primary avenues for restoration of water balance are fluid and food ingestion, with water from oxidation making a minor contribution.⁵ The volumes of water that individuals obtain from food and drinks are highly variable, although it is generally reported that the majority comes from liquids, with a smaller, although still significant, proportion from solid foods.⁶

Body water loss in humans results in fluid losses from both the intracellular and extracellular fluid compartments.⁷ The fluid losses, however, can cause very different effects on the remaining body water pools depending on the type of water loss that occurs.^{8,9} Hypotonic water loss, as can occur with sweating, results in an increase in body fluid tonicity, while isotonic loss causes a net fluid loss but no increase or decrease in body fluid tonicity. Hypertonic fluid losses, as can occur with the production of a concentrated urine, cause a reduction in body fluid tonicity.

ENDURANCE EXERCISE PERFORMANCE

For the purposes of this discussion, endurance exercise is defined as continuous aerobic exercise of more than 60 minutes in duration. The effects of dehydration on physiological function and exercise performance during endurance exercise have usually been studied either by inducing a certain degree of body water loss before the exercise task or by allowing dehydration to develop during the exercise. Clearly, each of these approaches may have different effects on the type of body water loss that develops (i.e. hypotonic, isotonic, or hypertonic, as described above), which may in turn influence the experimental findings. However, it has become apparent from the published literature that many of the physiological responses and exercise performance outcomes observed are remarkably similar regardless of the means by which the body water deficit is induced.

Cheuvront et al.¹ have recently undertaken an ex-

tensive review of published studies examining the effects of dehydration on exercise performance (Table 1). The available evidence led the authors to conclude that in situations of exercise in a warm environment (defined as

an ambient temperature greater than 30°C), dehydration to the extent of 2% to 7% of body mass consistently decreases endurance exercise performance. However, the extent of the performance decrements was highly vari-

Table 1. Effects of Dehydration on Exercise Performance. (Redrawn from Cheuvront et al., 2003.¹ Used with permission.)

Study	Conditions	Dehydration*	Performance Results
Adolph, 1947 ²³	Desert walk (21 miles); 31°C–39°C; NF (<i>n</i> = 13) or AL (<i>n</i> = 9)	NF = 6.3% AL = 4.5%	NF = 5/13 failed to complete walk (38%) AL = 3/9 failed to complete walk (33%)
Mudambo et al., 1997 ²⁴	Walk/run/obstacle course (3 h); 39°C/28% RH; NF (<i>n</i> = 18) or SF (<i>n</i> = 6)	NF = 7% SF = 2.8%	NF = 6/18 subjects failed to complete course vs SF; NF = increase in RPE compared with SF
Ladell, 1955 ²⁵	Bench step to exhaustion; 38°C/78% RH or 38°C/30% RH; <i>n</i> = 4; NF or F	No data	NF = ~20% decrease in walk duration; increased RPE compared with AL and F
Pitts et al., 1944 ²²	Walk 3.5 mph, 2.5% grade (5 h); 35°C/83% RH; <i>n</i> = 6; NF, AL, or F	No data	NF = ~60% decrease in walk duration; increased RPE compared with AL and F
Walsh et al., 1994 ⁴⁴	Cycle ergometer 70% VO _{2max} for 60 min, then 90% VO _{2max} to exhaustion; 32°C/60% RH; <i>n</i> = 6; NF or F	NF = 1.8% F = 0.0%	NF = 31% decrease in TTE and increased RPE compared with F
Below et al., 1995 ²⁶	Cycle ergometer 50% VO _{2max} for 50 min, then performance ride; 31°C/54% RH; <i>n</i> = 8; SF or F	SF = 2.0% F = 0.5%	SF = 7% decrease in performance compared with F
Barr et al., 1991 ²⁷	Cycle ergometer 55% VO _{2max} (6 h); 30°C/50% RH; <i>n</i> = 8; NF or SF	NF = 6.4% F = 1.2%	NF = 25% decrease in TTE compared with SF
Bachle et al., 2001 ¹⁰	Cycle ergometer 60 min performance ride; 21°C/72% RH; <i>n</i> = 10; NF or F	NF = 1.0% F = ↑ 0.5%	No differences in performance ride or RPE among trials
McConnell et al., 1999 ¹¹	Cycle ergometer 80% VO _{2max} for 45 min, then 15-min performance ride; 21°C/41% RH; <i>n</i> = 8; NF, SF, or F	NF = 1.9% SF = 1.0% F = 0.0%	No differences in performance ride among trials
McConnell et al., 1997 ¹⁴	Cycle ergometer at 69% VO _{2max} for 120 min, then 90% VO _{2max} to exhaustion; 21°C; <i>n</i> = 7; NF, SF, or F	NF = 3.2% SF = 1.8% F = 0.1%	NF = 48% decrease in performance ride compared with F only
Robinson et al., 1995 ¹²	Cycle ergometer performance ride (60 min); 20°C/60% RH; <i>n</i> = 8; NF or F	NF = 2.3% F = 0.9%	NF = 1.7% increase in performance ride compared with F
Fallowfield et al., 1996 ¹⁵	Treadmill run at 70% VO _{2max} to exhaustion; 20°C; <i>n</i> = 8; NF or SF	NF = 2.0% SF = 2.7%	NF = 25% decrease in TTE vs SF
Maughan et al., 1989 ¹³	Cycle ergometer 70% VO _{2max} to exhaustion; <i>n</i> = 6; NF or SF	NF = 1.8% SF = 2.0%	No differences in TTE between NF and SF

*Percentage of body mass. AL = ad libitum fluid; F = fluid; NF = No fluid; RH = relative humidity; RPE = rate of perceived exertion; SF = some fluid; TTE = time to exhaustion.

able, ranging from a 7% to a 60% decline in performance. A less-consistent result occurred when the endurance exercise was undertaken in temperate conditions. In these situations, dehydration by 1% to 2% of body mass had no effect on endurance exercise performance when the exercise duration was less than 90 minutes,^{10–13} but when it was more than that, performance was impaired.^{14,15} Therefore, one key conclusion that can be reached when endurance exercise performance is being considered is that an important level of dehydration is a water loss equivalent to 2% of body mass. Dehydration to this extent appears to reduce endurance exercise performance in both temperate and hot environments, especially when the duration of exercise is 90 minutes or more.

In summary, dehydration by 2% of body mass during exercise in a hot environment (31°C–32°C) clearly impairs endurance performance, but when exercise is performed in a temperate environment (20°C–21°C), dehydration by 2% of body mass appears to have a lesser and insignificant effect on endurance performance. These findings suggest that athletes should try to offset dehydration as much as possible when exercising intensely in a hot environment for durations approaching 60 minutes and longer. However, when the environment is temperate, athletes may be better able to tolerate 2% dehydration without significant performance decrement or risk of significantly added hyperthermia compared with exercise with full fluid replacement. In cold environments, dehydration by more than 2% may be tolerable.

MECHANISMS OF ENDURANCE EXERCISE PERFORMANCE DECREMENTS WITH DEHYDRATION

When dehydration has a negative impact on exercise performance, the mechanism or mechanisms whereby this occurs may be via increased cardiovascular strain, increased heat strain (hyperthermia), altered central nervous system function, altered metabolic function, or by a combination of these.

When body water content is decreased, an increased heart rate and decreased stroke volume is observed, indicating an increased cardiovascular strain. If the endurance exercise is taking place in a warm environment, then cardiac output may not be able to be maintained at a level that allows exercise to continue. Experimental work to investigate this has generally reported higher heart rates when negative fluid balance has developed (as a result of no fluid consumption) in a range of moderate to hot environmental temperatures (22°–33°C), and in both trained and untrained subjects.^{16–20} Montain and Coyle¹⁸ demonstrated that the extent of dehydration induced (over the range of 1%–4% of body mass) was directly related to the magnitude of the heart rate in-

crease and the decrease in stroke volume observed. Subsequent to this, Gonzalez-Alonso et al.²¹ demonstrated both independent and synergistic decrements in cardiovascular function following dehydration, heat stress, and a combination of the two.

The increased cardiovascular strain seen during exercise when dehydration is present has also been shown to coincide with an increase in perceived effort.^{14,15,22–27} Therefore, it is possible that cardiovascular strain may impair endurance performance by decreasing the motivation to exercise.

It has also been proposed that there is a “critical core temperature” that results in exercise exhaustion and the cessation of exercise.²⁸ The hypothesis is that when this core temperature is achieved, the central nervous system reduces the drive to exercise in order to reduce heat production (and the exercise-induced hyperthermia that may result) and protect neuronal function. The authors have reported that, at least in the experimental setting, this core temperature is within a narrow range of around 39.5°C to 40°C.^{28–30} In support of a critical core temperature limit, there is evidence that hyperthermia may diminish the drive to exercise and reduce exercise tolerance time, possibly through a central nervous system route.

The electroencephalogram activity of the frontal brain in cyclists has been investigated in both a hot (42°C, 18% relative humidity) and a cooler (19°C, 40% relative humidity) environment during exhaustive exercise.³⁰ This process involves measurement of low (α) and high (β) band frequencies, which vary in their activity during situations of sleep or drowsiness. There was little change in α -band activity recorded throughout exercise, while β -band activity became progressively lower. Further, the α/β index was highly and significantly correlated with core temperature ($r^2 = 0.98$; $P < 0.01$). Similarly, α and β measures have been shown to be highly correlated with ratings of perceived exertion.³¹ A reduced voluntary force-generating capacity of muscles of the quadriceps and forearm have been shown as the core temperature increases to 40°C.³²

Finally, it is feasible that exercise endurance and performance are impaired when dehydration is present as a result of the effects on muscle metabolism. Hargreaves et al.³³ demonstrated that muscle glycogen use was reduced by 16% during prolonged exercise compared with a trial in which no drink was consumed. This increased muscle glycogen utilization in a dehydrated situation probably results from higher body temperatures, increased catecholamine levels, or a combination of the two.³⁴ However, if heat stress is sufficient and cardiac output is reduced (as described earlier in this section), blood flow to active skeletal muscles may be reduced,³⁵ which in turn could make it difficult to sup-

port adequate aerobic metabolism, meaning that exercise intensity must be reduced.

In conclusion, the current research indicates that dehydration, because of its effects on the circulation, makes hyperthermia more difficult to cope with and is the main factor in early fatigue. In most studies investigating the effect of hydration status on endurance exercise performance that have reported thermoregulatory and cardiovascular variables, the reduction in exercise performance was associated with higher core temperatures, heart rates, and ratings of perceived exertion.

STRENGTH AND POWER PERFORMANCE

When body water loss has occurred, various effects on neuromuscular function and short-term power have been reported. Muscle strength during a muscle contraction is determined by the ability of the nervous system to recruit motor units in concert with the number of muscle contractile units in cross-section. Therefore, it is of interest in this section to consider whether a reduction in muscle water has the potential to alter force generation capability or energy production when maximally stimulated.

The majority of published studies indicate that dehydration up to a loss of 7% of body mass can largely be tolerated without a reduction in measured maximal isometric or isotonic muscle contractions.³⁶ When muscle strength reductions have been noted with dehydration, the upper body muscles appear to be affected to a greater extent than the lower body muscles. Also, the published evidence suggests that there is a greater likelihood of a strength reduction if dehydration is induced as a result of prolonged food and fluid restriction,³⁷ and questions have been raised as to the role that factors other than dehydration per se may have in the findings reported.³⁸

When maximal aerobic power has been investigated with regard to hydration status, the findings suggest that when hypohydration of less than 3% of body mass is present, there is no effect on maximal aerobic power, but when the dehydration increases to between 3% and 5% of body mass, power reductions have been recorded.³⁶ Therefore, the available evidence suggests that body water loss equivalent to 3% of body mass may be the critical level when axial aerobic power is being considered. Also, as seems to be the case with endurance exercise performance, decrements in maximal aerobic power appear to exist, with slightly lower levels of dehydration when the environmental conditions are hot.³⁹

SKILLS PERFORMANCE

Many sports such as football, rugby, basketball, hockey, and tennis are stop/start in nature and consist of

prolonged periods of exercise with repeated intermittent high-intensity bursts interspersed with lower-intensity exercise. Successful performance in these sports involves fatigue resistance, but also relies on cognitive function for decision making and proper execution of complex skills. This makes assessment of sport performance challenging to study. However, a number of protocols have been developed that have attempted, among other things, to investigate the effect that hydration status may have on aspects of sports performance. In many of the studies undertaken in this area, the protocol used involves allowing dehydration to develop in one trial and preventing it in another by provision of drinks. However, the drink provided has frequently been a sports drink, and therefore, the influence of carbohydrate or other components in the drink on the outcomes measured cannot always be distinguished from any effects due to prevention of dehydration.

Williams et al.⁴⁰ have developed a shuttle-running test aimed at simulating the intense “stop and go” nature of sports such as football. The same group has reported that fluid replacement with flavored water sufficient to limit body mass loss to approximately 1% prevented a reduction in soccer skill performance compared with performance when body mass was reduced by more than 2%.⁴¹ In a study investigating motor skill performance during cricket bowling,⁴² subjects were dehydrated by 2.8% of their body mass and their performance was compared with that when they had drunk flavored water and limited their dehydration to 0.5% of body mass. There was no influence of dehydration on bowling speed, but bowling accuracy, as determined by line and distance, was significantly worse when undertaken in the dehydrated state.

As discussed earlier, significant levels of hypohydration can be induced in healthy volunteers by relatively short periods of voluntary fluid restriction. Even though the dehydration induced is relatively minor, it seems sufficient to cause subjects to report feelings of headache, tiredness, reduced levels of alertness, and greater difficulty concentrating.⁴³ Clearly, all of these may impact sporting skills performance.

PANEL DISCUSSION

Eric Jéquier: Obviously, impaired thermoregulatory functions may have an effect on performance, and I just wanted to add another mechanism that you have not mentioned with reference to hyperthermia. You mention that hyperthermia alone may not decrease cardiac output or impair blood pressure. But what is very interesting during hyperthermia is that you have a skin vasodilatation with increased skin blood flow and a concomitant decrease in muscle blood flow, so even though the

cardiac output may not be changed, the blood flow to the muscle can be reduced, explaining part of the decrease in performance.

Susan Shirreffs: Yes, these studies do show changes in cardiac output and blood pressure, but we can cope with them. It's the dehydration and hyperthermia together that are far more difficult to cope with during exercise.

Irwin Rosenberg: Is it your understanding that the reason high temperature adds to the sensitivity of the effect of dehydration is because under those circumstances it is, in fact, the core temperature of the body that is changing and so you have the double effect of insufficient water?

Susan Shirreffs: Certainly, as the core temperature goes up there is far more competition for the cardiac output. There is the cardiac output required to maintain the exercise and at the same time blood flow to the skin to dissipate heat is required. In terms of the exact mechanism whereby increasing core temperature has an effect on endurance exercise performance, I don't think we have a clear single mechanism as yet. We do see changes in central functioning and changes in blood-brain barrier permeability, and these may be relevant.

Irwin Rosenberg: On the question of what is normal and what is optimal, how good are the data, and are there enough data to really be confident that 2 liters or 2.8 liters of dehydration represents a true threshold? How much data are there to determine whether there is some gradation of function at lower levels of dehydration?

Susan Shirreffs: There are studies with dehydration between 1% and 2% body mass loss, showing that performance effects really are mixed, many of them showing no effects on performance. It's really once you hit 2% body mass loss and above, and there are quite a lot of studies at these levels, that the greater the extent of the dehydration, the greater the performance detriment. I would say that the data are reasonably good.

Irwin Rosenberg: So there are not even interesting trends at smaller levels of dehydration?

Susan Shirreffs: I would say no.

Irwin Rosenberg: Do all you other physiologists agree with that?

Michael Sawka: I think the data are inconclusive because, first of all, as from the earlier discussion, a lot of people use different methods and different assessments of the initial hydration status. I think that most of the fluid physiologists would agree that there is no one threshold hydration level. It will fluctuate a bit between a liter or two. A good rule of thumb given to the athletic community is that at a 2% loss of body weight, you start seeing very consistent reductions in performance, and as you decrease below that you get greater performance reduction. I am left with the impression that hypovolemia

is the primary mechanism of reduced performance. But osmolality by itself will have an important impact, because what you see is that plasma hyperosmolality is what's mediating the change in sweating, particularly the threshold at the onset of the sweating response. As you dehydrate, the reason you're getting proportionally hotter is that your thermoregulatory system is regulated down to conserve body water. If you have reduced evaporative cooling you get hotter. So osmolality is very important, and I certainly agree with Dr. Shirreffs that the cardiovascular response is a very important component of it, but there are other mechanisms. We do know that as you get hotter, which we know will occur with dehydration, you increase glycogen breakdown, so for a very long endurance event, muscle glycogen depletion is greater. Interestingly, though, if you dehydrate you replenish glycogen at the same rate. We also know that as you get hotter, there is probably a central nervous system component because brain temperature is increased, and, as Lars Nybo's lab showed (Nybo L, Secher NS, Nielsen B. Inadequate heat release from the human brain during prolonged exercise with hyperthermia. *J Physiol.* 2002; 545:597–704.), brain temperature is probably higher than blood temperature. So as the brain gets hotter, there does seem to be some mechanism that's decreasing the drive to the muscles to contract, because when you do muscular stimulation, they can generate that force back. We really don't have any understanding of what those mechanisms are, but they probably occur not only in heat and endurance, but also during exercise while dehydrated in a temperate environment. If you have subjects exercise in a fairly cool environment while dehydrated, you still will see this performance reduction, although perhaps not as great. We have some idea of the basic mechanisms, but it is quite clear that there is a lot more involved.

Irwin Rosenberg: If you're trying to protect physical performance, do you say, well let's make sure that body water losses are never more than 1% because when you get to 2% you start to have these demonstrable effects, or should it be never more than a half percent? Is 2% such a useful number that it can be used as a cut-point, or as a target for the prevention of physical performance loss?

Susan Shirreffs: You need to think about the environment you are in as well. If it is a cold day, say 2°C to 5°C, then you can probably cope with greater levels of dehydration than you can in a warm or hot environment.

Antonio Dal Canton: In view of the great importance that a decrease in plasma volume has in reducing performance due to dehydration in endurance exertion, in your experience, is there any difference when rehydration is made by giving salt in addition to water? In that case, the expansion of plasma volume should be much more effective.

Susan Shirreffs: Yes, there is a lot of published information on that. If someone is dehydrated because of sweat loss during exercise, then they have lost a reasonable amount of salt in their sweat. Sweat is hypotonic, so serum osmolality has increased. But if you just replenish with plain water, a diuresis will occur and much of the ingested water will be lost again.

Irwin Rosenberg: So what is the importance of the kinetics of water uptake in rehydration? Whether the presence of sodium or glucose increases the speed with which water uptake replenishes lost volume?

Susan Shirreffs: There is the role of sodium/glucose co-transport in promoting water absorption in the intestine. But then there is a secondary role of retaining the water in the body.

Friedrich Manz: Subjects performing hard physical work in the heat usually lose body weight, as they drink markedly less fluid than they lose in sweat, even if unlimited drinking fluid is at hand. In 1947, Adolph called this loss of body mass and total body water “voluntary dehydration.” In a field study in 38 coal miners during 111 working shifts, we observed a mean loss of body mass of 1.5% or 1218 g and of total body water of 1034 mL. According to our calculations, the loss of total body water is due to the mobilization and excretion of physically bound water—not altering plasma tonicity and, therefore, not stimulating renal mechanisms to excrete or preserve water. One important source of the isotonic loss of body water is the diminution of the water pool physically bound to glycogen during glycogen consumption. Another source is the isotonic contraction of extracellular volume due to the non-substituted sodium excretion in sweat or urine and the simultaneous water loss in the amount of the loss of extracellular volume. In our discussion, we should discern between the size of the total body water pool and the regulation of body water tonicity. Not every loss of total body water is accompanied by an increased plasma osmolality and the sensation of thirst.

Susan Shirreffs: Yes, there are issues to be considered when muscle glycogen is utilized, with release of water that is bound to it.

Friedrich Manz: For the public, the loss of body weight during an activity is synonymous with loss of body water and dehydration. I think that we should tell the public that these terms have a different meaning. This has practical consequences. It is nonsense for a long-distance runner to keep his body weight at the level of the start of the race. He remains really well hydrated although he slowly loses weight.

Irwin Rosenberg: Is some of that interval between no loss of body mass during exercise and 2% loss, and the fact that it's hard to demonstrate a physiological deficit or a performance deficit, is some of that related to

the buffering effect of the release of water internally from glycogen breakdown?

Susan Shirreffs: Possibly some of it is, yes.

Irwin Rosenberg: Is there any way to quantify that?

Susan Shirreffs: There is still debate as to how much water is bound with glycogen. I think we still don't have agreement on that, so I would say, no, there is no good way to easily do it.

Antonio Dal Canton: I would like to go back to the problem of voluntary dehydration. When you lose sweat, you lose hypotonic fluid, which means that you lose more water than salt, but you lose also salt. When you drink pure water, you will rapidly dilute plasma osmolality. Plasma osmolality is the main thrust to thirst. So, even having gained less water than the total amount that you have lost, you will stop drinking and you will gain the remaining part of water only when you also gain salt—that is, when you eat something. That's the reason why you can remain apparently dehydrated even if you have been given water *ad libitum*.

Susan Shirreffs: Yes, there are many studies showing that if people are dehydrated and are then given different drinks *ad libitum*, either plain water or water with some sodium, they will drink less of the water. Their thirst mechanism will switch off.

Antonio Dal Canton: Even if they are allowed to take salt?

Susan Shirreffs: No, if the drink has salt in it, they will drink a larger volume. Yes, there are studies published on that.

Eric Jéquier: I want to come back to Dr. Manz' comment on the use of glycogen. I think it might be a rather important component of this so-called rapid weight loss, at least during intense exercise. You mentioned that you are not sure of the relationship between glycogen and water, but I think there are some rather good data indicating that when you use one gram of muscle glycogen or liver glycogen, it corresponds to a weight loss of four grams.

Susan Shirreffs: People debate that.

Eric Jéquier: Yes, but even if it is a little overestimated, you can calculate that during intense exercise, it might constitute an important component of this weight loss, because since 100 grams of glucose or glycogen can be lost in rather a short period of time, it will lead to a 400-gram weight loss. When we speak of 1% of body weight loss, it may be a component without being related to dehydration.

Susan Shirreffs: But, remember, in many of the endurance exercises, people are working at low exercise intensity and so it is not the rapid glycogen usage that we would see in higher-intensity exercise.

Eric Jéquier: I was thinking of athletes during the intense part of their exercise. When you speak of fatigue

at the end of the performance, obviously you use glycogen in these conditions.

Michael Sawka: For most situations where you see exercise performance reduction with dehydration, glycogen depletion is not a limiting factor. But you do raise a good point, and it has caused confusion, particularly with the South African studies. A lot of athletes' glycogen load, as they reduce the water and the glycogen bound to it, probably results in an overestimation of the level of dehydration.

Irwin Rosenberg: If we are trying to conceptualize an equation that tries to describe the factors that are included in water requirement, the degree of how much dehydration can be tolerated in order to preserve physical function, it seems that somewhere in that equation the calculation of the amount of energy going into exercise, and therefore some estimate of glycogen breakdown, would have to be part of the concept, even if it is not true that this is limiting.

Michael Sawka: If you just look at glycogen breakdown, which has been studied, it is very marginal. You've got to look very hard in terms of increase. If you are talking about something aside from the laboratory setting, like an athlete in whom you are really not controlling water status and glycogen and doing all the careful measurements beforehand, and you super-load with carbohydrates and the athlete goes out and exercises, certainly they're going to lose this bound glycogen in part of the reduction in body weight. If you just went by body weight alone, it would give you a spurious idea of exactly how much your total body water decreased in terms of reduction below the euhydration level. So, if you're building a model and you're trying to account for it based upon body weight and level of dehydration, then, yes, that's something that might be difficult to account for. If you're saying that you're looking at a model in terms of mechanisms of fatigue, that glycogen depletion is not a limiting factor in most of those experiments, studies that have been designed to look at glycogen depletion as a limiting factor show very modest effects of dehydration.

Larry Armstrong: To put this into perspective, if you look at someone who's running a 1500-meter race versus an ultra-marathon, the glycogen depletion at the high intensities may be important for performance, but that is probably not a dehydration or water effect. Now, in an ultra-marathon, where you have someone who's maybe out for 19 hours, and if they're losing about one or two liters per hour, then their total sweat loss is 19 to 38 liters, which is much more when you consider how much glycogen there is in the entire muscle mass of the body and how much water is bound to that. Typically, when an athlete super-compensates with water and with carbohydrates, they gain two or three pounds, which is a

few pints, compared with 19 to 38 liters. It is considerably different, and there's a dehydration effect in those longer endurance events.

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