Hydration and Performance

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Abstract

While often overlooked, hydration state plays an important role in performance and function. A hypohydrated state can bring about decrements in performance in nearly every aspect; 5.5 ± 1.0% for strength, 5.8 ± 2.3% for power, 8.3 ± 2.3% for endurance, and various decrements to flexibility. Hypohydration likely also stunts recovery, with exercise induced muscle damage and exercise associated muscle soreness being worsened. While no research suggests decrements in cognitive abilities, hypohydration encroaches on mood and potentially rate of perceived exertion (RPE). A state of dehydration may use up glycogen storage quicker, leading to inferior performance outcomes. Contrary to popular belief, regular consumption of creatine only increases body weight over a short term period. There is much debate on hydration protocols, mainly around drinking ad libitum or on a schedule. Hydration needs are highly dependent on the individual, and should be assessed on a case by case basis.

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Introduction

Fifty-five to sixty percent of the human body is composed of water, making it an invaluable resource to replenish and regulate (United States Geological Survey, 2019). Water plays structural, metabolic, transport, and temperature control roles in the body (Serra-Prat, 2019). Cellular hydration status may also have a role in regulating metabolism and gene expression (Cheuvront et al., 2020). Approximately 76% of striated muscle is composed of water, indicating its necessity in abundance in musculature (Lorenzo et al., 2019). Moreover, water is the solute that allows blood and nutrients such as oxygen to flow through the body, making it indispensable for survival functions. Yet many do not give second thought to their body's hydration state.

A myriad of factors influence an individual's state of hydration, encompassing both individual and environmental. The level of dehydration a person may experience is approximately proportional to the degree of total stress imposed on the body (Greenleaf, 1992). Individually, certain biopsychosocial factors may cause dehydration, such as social customs, stress, and biological differences (Greenleaf, 1992). Physical activity and exercise are common contributors to dehydration, as it induces heavy muscular exertion and rapid heart rate, resulting in perspiration. Environmentally, excessive heat and humidity causes dehydration as well. Even with the many such factors that threaten dehydration, thirst is not always a sufficient stimulus to keep humans hydrated, meaning it is important to understand situational factors to ensure safety and optimal performance (Greenleaf, 1992).

The state of proper hydration is referred to as euhydration and can be described in a sinusoidal wave as shown in Figure 1 (Greenleaf, 1992). Water is typically consumed in bouts, and body water content fluctuates throughout the day. The two bodily factors that contribute to dehydration are the loss of water and the lack of intake of water. Losses occur with sweat, urination, respiration, and defecation. If a state of dehydration continues for a long enough time, the person is considered to be in a state of hypohydration (Casa, 2004). While hypohydration refers to the state, dehydration refers to the process of losing water. The terms “dehydration” and “hypohydration” are often used interchangeably, as it usually does not alter the general meaning.

There are three types of water loss that may occur through dehydration (Shirreffs, 2005). Hypotonic water loss results from sweating, causing there to be an increase in body fluid tonicity. Isotonic water loss occurs when there is a net fluid loss but no increase or decrease in body fluid tonicity. Hypertonic water loss is when there is a reduction in body fluid tonicity such as when concentrated urine is excreted.

Research suggests that a 1-2% loss of water of total body weight at one time is to be expected and normal, but any more should be avoided, as negative effects in performance and function will likely occur. There is a general consensus in the literature signifying 2% of body weight loss of water to be the threshold for detrimental dehydration. However, temperature may play a large factor, as in cold or temperate conditions (5°C- 22°C), many individuals can handle body water losses of about 2% of body weight without much detriment in health or endurance exercise performance (Shirreffs, 2005). When temperatures reach 30°C or more, that 2% of body weight loss becomes a much bigger problem and increases chances of heat injury. Detriments to the body can be seen not only in the muscular system but in the gastrointestinal and central nervous system as well (Casa, 2004). In addition to performance decrements, hypohydration may increase odds of physical injury, as it plays a role in increasing stress levels, which leads to elevated cortisol levels, which in turn are linked to increased risk of injury (Puga et al., 2023; Perna and McDowell, 1995). Though not a direct association, workplace accidents and injuries increase during the summer months when fluid turnover is highest and hypohydration is the most likely to occur (Ely et al., 2012). On the contrary, if too much fluid is to be consumed, hyponatremia may occur, with sodium levels dipping below 130 mmol/ L (Casa, 2004). This could stem from an excessive intake of fluids or an ingestion of low-sodium fluids. Over ingestion of water through hyperhydration and the resulting hyponatremia come with their own set of problems, including dizziness and vomiting. In worse cases, cerebral swelling may occur, leading to death by brain herniation (Cheuvront et al., 2020). Thus, a state of euhydration is essential for survival, well-being, and performance. This literature review will delve into the effects of hypohydration on exercise and functional performance, along with practical applications to avoid the negative effects of hypohydration.

Hydration and Exercise Performance

Strength, Power, and Endurance

There is plenty of data and research on the topic of hydration and exercise performance, particularly for endurance (James et al., 2017). While rich in research, much of it is done with scattered variables, demographics, and methods. A review by Judelson et al. in 2007 was the first to tackle this issue by compiling a systematic review with special focus to standards pertaining to factors that may skew data (Judelson et al., 2007). Three main points are mentioned: exacerbating factors, masking factors, and other influences such as psychological factors.

Exacerbating factors are variables that may make the effects of hypohydration seem more extreme than they actually are. A notable example brought forth is that of wrestlers (Judelson et al., 2007). It is common for wrestlers to cut bodyweight to meet their competition weight. Many studies do not account for the lost weight to be partially from water and partially from the decreased consumption of food or defecation. As such, the wrestlers are in a caloric deficit, confounding with hypohydration. Another example is research done in extremely hot environments. Independent of hydration, increasing muscle and body temperature above specific thresholds reduces muscle function, which limits work capacity and promotes fatigue (Judelson et al., 2007). It is very common for researchers to purposefully place subjects in hot environments as part of the study because it encourages perspiration. It is also a topic of interest because many performance settings inevitably expose the individual to extreme heat. However, the use of a hot environment may produce compounded deleterious effects for exercise performance on top of the hypohydration. While utilizing heat may not be optimal for elucidating the effects of purely hypohydration, Judelson et al. (2007) states that using exercise to induce hypohydration may not be optimal either because the resulting muscular fatigue may confound with the true effects of hypohydration as well. Judelson et al. (2007) recommends that if exercise is to be used as a method that the exercise should be done in the evening followed by a night's rest with no water consumption. Subsequently, the testing should occur the morning after. Savoie et al. (2015) argues that this is akin to water deprivation and is categorized as such.

Opposite of exacerbating factors, masking factors are variables that downplay the effect of hypohydration. A prime example of this is an individual’s training state. Caterisano et al. (1988) found that endurance athletes were able to complete more quadriceps extensions than their non-endurance trained counterparts while hypohydrated. It is proposed that hemodynamic adaptations allow endurance athletes to have an extra reserve of water to offset the fluid shifts of dehydration. The fact that lean body mass has a significant inverse relationship with strength reductions backs up such a claim (Schoffstall et al., 2001). It was found that there was a strong association between lean body mass and bench press strength, with detriments from dehydration resolved after two hours of rest and rehydration. The more lean body mass, the more fluid reserves an individual possesses. As such, it is shown that any condition that increases total body water whether it be nutritional or physiological, helps to counteract the deleterious effects of hypohydration (Savoie et al., 2015).

Lastly, Judelson et al. (2007) mentions the possibility of a subject’s experience with exercising while hypohydrated as being a confounding variable as well. However, there is no scientific literature to back this claim. Further, if this were to be the case, the results would likely arise from psychological factors rather than physiological.

Judelson et al. (2007) screened out all of the studies that they believed had the aforementioned confounding variables before performing their review, leaving 11 peer-reviewed sources. What they found was that under a state of hypohydration of about 3 to 4% of total body mass, muscular strength experienced about a 2% decrease, muscular power experienced about a 3% decrease, and high intensity endurance experienced about a 10% decrease in output (Judelson et al., 2007). The stark difference in drops in performance between high intensity endurance and the other two measures makes sense because of the large body of literature showing endurance to be a highly affected performance marker under hypohydration (James et al., 2017). Moreover, there is a direct relationship between magnitude of hypohydration-induced performance decrement and exercise duration (Cheuvront et al., 2003).

The mechanism of altered endurance exercise performance from hypohydration involves increased cardiovascular strain, altered central nervous system (CNS) function, and altered metabolic function (Shirreffs, 2005). Hypohydration reduces total plasma volume, which subsequently increases submaximal heart rate and decreases maximal cardiac output (Judelson et al., 2007). Decreased blood leads to a gross decrease of blood for nutrient delivery and waste removal. This is potentially why endurance exercise is affected to a greater extent than strength and power movements. Further, it is also proposed that decreased blood may reduce buffer capacity, leading to difficulties in maintaining optimal pH (Judelson et al., 2007). Endurance exercise relies on the aerobic system for ATP production, meaning blood volume is important for transport of oxygen, while strength training is anaerobic, relying on the phosphocreatine pathway and glycolysis (Judelson et al., 2007). Because of the length of exercise and the oxygen and metabolite removal demands of the body in endurance exercise, endurance exercise is affected to a greater degree than anaerobic exercises.

The cause for performance decrements in short burst exercises is likely caused by altered metabolic profiles. As explored later, cell volume, which is greatly affected by hydration, acts as a metabolic and hormonal signal (Haussinger et al., 1993). Altered carbohydrate metabolism may be the cause for potential effects on performance, leading to changes in intramuscular stores of ATP and creatine phosphate (Judelson et al., 2007). However, research is conflicting and limited, and the current consensus is that carbohydrate metabolism is not the cause for negative effects of hypohydration on anaerobic performance.

While changes in strength are not as marked as endurance, when muscle strength reductions are noted, the upper body muscles seem to be affected to a greater extent than the lower body (Shirreffs, 2005). This could potentially be due to muscle fiber distribution differences between the upper and lower extremities, but more research is needed to make any solid conclusions.

Another possibility for performance decrements from hypohydration is that rather than changes in the muscle itself, the problem lies within the neuromuscular system as a whole. Perhaps a diminished ability for the central nervous system to recruit motor units is the cause for decreases in performance. However, there is a gap in literature, meaning that there is currently not enough knowledge to answer this question.

The systematic review compiled by Judelson et al. (2007) was the first of its kind and the only comprehensive investigation until Savoie et al. (2015) produced a meta-analysis eight years later in 2015. The results were of similar nature. Twenty-eight studies were chosen, and it was shown that endurance suffered by 8.3 ± 2.3% and muscle strength decreased by 5.5 ± 1.0%. Anaerobic power was significantly impaired by hypohydration by 5.8% ± 2.3%. Anaerobic capacity did not show statistically significant changes at -3.5 ± 2.3%. What’s of note is that vertical jump ability increased in hypohydrated individuals. Interestingly, such was hypothesized by Judelson et al. (2007). Vertical jump increased by .9 ± 1.8%, although the figure wasn’t statistically significant (Savoie et al., 2015). Further, it was found that compared to passive dehydration methods such as the use of heat, active dehydration protocols, such as exercise, decreased performance by 4.8 ± 1.8%. While Judelson et al. (2007) had proposed such a decrease from exercise confounding with hypohydration, it was quantified by Savoie et al. (2015). This confirms that studies ought to use either passive dehydration methods or allow for a night of rest after using an exercise protocol to achieve the most accurate results. Trained individuals also showed a lesser decrease in muscle performance compared to untrained individuals by 3.4 ± 1.7%. Thus, it can be stated that to avoid the negative effects of hypohydration during training, it is advantageous to increase lean muscle mass and to consistently train both aerobically and anaerobically. As aforementioned, training in heat may also produce a psychological edge for performing under similar conditions. Experiencing repeated cell shrinkage may produce positive adaptations in modulating gene expression, leading to greater tolerance to hypohydration (Cheuvront et al., 2020).

While the body of research done in regards to hypohydration and exercise performance is extensive, James et al. in 2017 brought forth skepticism in regards to the validity of prior research, including the previously mentioned studies. The reasoning is that research pertaining to hydration typically uses overt methods in inducing hypohydration, meaning that subjects are usually aware of which side of the trial they are undertaking, whether it be the control or the hypohydrated group. Such a variable may confound the data, skewing it to show that hypohydration negatively affects performance, when in reality it could stem from psychological components in the procedure. James et al. (2017) cites two relatively recent studies by Cheung et al. (2015) and Wall et al. (2013) that employed blind testing strategies in elucidating the effects of hypohydration on performance by using intravenous hydration. Both showed similar results in that there was little difference between the control group and the hypohydrated group. Neither study allowed oral fluid ingestion, which James et al. (2017) hypothesized could be important for thirst perception and ultimately exercise performance. However, the intravenous hydration would bypass oral fluid ingestion, which is important to thirst perception and potentially exercise performance. To disallow oral fluid ingestion, James et al. (2017) tested seven subjects using a gastric feeding tube inserted orally. Seven subjects were chosen because prior research indicated that six would be sufficient to reject the null hypothesis for the primary outcome of endurance performance. Subjects completed two trials without the knowledge of not receiving any fluid for one of them. Contradictory to the Cheung et al. (2015) and Wall et al. (2013) studies, the results showed that even when blinded, hypohydration impaired endurance performance by 8% (James et al., 2017). While the studies by Cheung et al. (2015) and Wall et al. (2013) should not be dismissed, it is likely acceptable to acknowledge studies that do not employ blind testing strategies.

Silva et al. (2014) produced an intriguing observational study on the effects of body composition over the course of an athletic competition season of six to eight months for highly trained athletes. Prior research had shown power and grip strength reduction in judo athletes that experienced decreases in intracellular water (ICW). Participants were selected from a diverse pool of sports, with basketball, handball, and volleyball. A third of the subjects were female. Females were assessed during the luteal phase and were not reported to be taking any oral contraceptives. Diet, strength, power, and various body mass measurements via DXA (dual energy x-ray absorptiometry) scans were taken prior to the season and during the main competitive part of the season.

The results showed an increase in lean mass, total body weight, and extracellular water (ECW). The mean leg strength and squat and countermovement jump height increased as well. There was not a significant difference in ICW. Counterintuitively, only ICW was shown to be significantly related to leg strength and jump heights. The authors grouped the athletes into those with strength and power changes of 3% or more and those with less and found that athletes who showed an increase in ICW also displayed improvements in performance metrics. The authors point out that "cell swelling theory" could have acted as an anabolic signal, increasing performance. Another possibility lies in that each gram of glycogen is bound to three to four grams of water, meaning, athletes who rapidly replenished their glycogen stores could have had an advantage in an increase in ICW.

Flexibility

While there is much literature on the effects of hypohydration on exercise performance such as endurance and strength, there is very little on the topic of flexibility. This may be surprising to some, as many treat hypohydration as a precursor to tight muscles. Indeed, in vitro studies have demonstrated that human collagen fibers stiffen when dehydrated, reducing its ability to resist deformation, elongation, and compression (Haut and Haut, 1996). However, there are few studies directly studying the effects of hypohydration on flexibility.

Ullucci et al. (2017) attempted to fill the gap in flexibility literature by investigating the link between dehydration and various flexibility metrics in 19 male collegiate age runners. The following were tested: posterior leg stiffness (PLS), hamstring flexibility, and straight leg raise range of motion (SLRROM). According to Ullucci et al. (2017), these measures are linked to athletic performance and risk of athletic injury. It can be surmised that if these metrics are decreased through hypohydration, that performance will suffer and injury risk will increase.

The results indicated a clear difference between the dehydrated and euhydrated groups, with the sit and reach test being nearly 4 cm more and the terminal straight leg raise (TSLR) being 9 degrees more for the euhydrated group. To quantify posterior leg stiffness, passive resistance was plotted against degrees of movement as a resultant variable. Accordingly, a smaller slope indicated passive resistance to movement increasing at a slower rate per degree of SLR compared to a steeper slope. Hypohydration increased this slope to a significant degree, indicating that dehydration made the subject's legs stiffer. The authors reasoned that euhydration lubricated and allowed for extra space within the extracellular matrix, allowing for there to be less friction on the cellular level, creating more mobility on a macro level.

Hypertrophy

With muscle composed of nearly 80% water, it is clear that water is a vital aspect of muscle volume and that it is desirable to have large levels of intracellular water to create an appearance of larger, fuller musculature. However, there is little direct evidence linking hydration levels and muscular hypertrophy.

There are speculations suggesting that cellular hydration state acts as an important factor in protein anabolism and catabolism, thus affecting hypertrophy. Haussinger et al. proposed in 1993 that cellular swelling is linked to anabolism and proliferation, and cellular shrinking is linked to catabolism. Changes in cell volume are primarily sensed by osmoreceptors, which are specialized neurons that detect osmolality and encode this information as electrical signals to send to the hypothalamus (Cheuvront et al., 2020). In the liver, the swelling of cells inhibits the breakdown of glycogen, glucose, RNA, DNA, and protein. If the cell is to undergo shrinking, the opposite metabolic pattern is triggered and results are seen within minutes. The loss of cell water leads to crowding of molecules and organelles and pleiotropic effects (Cheuvront et al., 2020).

Such may lead to DNA damage, mitochondrial dysfunction, oxidative stress, or cell death. Hormone-induced changes in cellular hydration can be seen as another way for cells to communicate and signal change. Changing the hydration state may act as a way to signal modification of cellular function. This regulation of protein turnover has been shown in rat and human liver cells, but may also apply to human skeletal muscle cells. (Haussinger et al., 1993).

More than anything, it is likely that the effects of hypohydration on hypertrophy are not direct, but secondary due to the effects of not being able to efficiently train. Hypertrophy is a result of intense training with high volume at times, and if an individual is not prepared to handle such training sessions due to hypohydration, it will likely hamper their desired effects of hypertrophy. Even small effects of hypohydration may compound over the course of an entire workout, leading to a decrease in mechanical stimuli, leading to potentially not maximizing muscular hypertrophy (Gann et al., 2020).

Exercise Induced Muscle Damage and Delayed Onset Muscle Soreness

Exercise induced muscle damage (EIMD) is a phenomenon that is characterized by loss of skeletal muscle function and soreness up to 14 days after the initial exercise bout (Owens et al., 2018). EIMD is more likely to occur when novel movements or training interventions are implemented, if training volume exceeds previous experience, or if repeated contractions involving stretch are performed (Allen, 2004). As the name suggests, EIMD is the result of structural and contractile properties of the muscles being disrupted or damaged (King and Baker, 2020).

There is a limited pool of research when it comes to the effects of EIMD and recovery. The available literature suggests that hypohydration may negatively affect recovery (King and

Baker, 2020). During exercise, there are many osmotic fluid shifts both intracellularly and extracellularly. Gross dehydration may reduce blood flow to muscle, creating risk for ischemia related damage (King and Baker, 2020). Further, osmotic changes in muscle signal reactive oxygen species (ROS), which can be exaggerated through hypohydration. The signal is likely to be exaggerated when eccentric contractions are repeated or if exercises that induce EIMD or prolong recovery are done. At higher levels of hypohydration of 4-5% body mass loss, blood viscosity is increased, causing even more ROS production and red blood cell rigidity (King and Baker, 2020). Increased ROS may injure the sarcolemma, cytoskeleton, and DNA of cells (King and Baker, 2020). While this may seem negative, ROS production should not be avoided completely, as it is needed for adaptation to exercise and dehydration.

While there are many facets to study or consider between hypohydration and EIMD, the question most pertinent is whether EIMD is exacerbated with hypohydration and if it prolongs recovery. King and Baker (2020) discuss three studies. Yamamoto et al. (2008) tested blood biomarkers in a squat study where exercise heat stress and water deprivation were the main variables. The elevation in lactate, creatine kinase, and myoglobin were similar between the dehydrated group and euhydrated groups 48 hours post exercise. On the other hand, Seifert et al. (2015) tested similar biomarkers with creatine kinase, myoglobin, and cortisol in alpine skiing, and found that they were all significantly elevated when fluid wasn’t replaced during the activity. Similarly, Ozkan and Ibrahim (2016) studied wrestlers cutting weight for competition in various ways. The results showed that the hypohydrated wrestlers had higher levels of blood biomarkers (aspartate aminotransferase, blood urea nitrogen, LDH, and creatine kinase) than the euhydrated group. Although these studies measured blood biomarkers of dehydration and muscle damage, no data was collected on force output or perceptions of muscle soreness.

An aspect of EIMD, delayed onset muscle soreness (DOMS) is the occurrence of muscular pain and other symptoms experienced one to four days after exercise (Cleary et al., 2006). Pain, tenderness, and decreased strength are common aspects in DOMS. While not necessarily an objective measure of performance inhibition, DOMS can inhibit performance or individual work capacity. DOMS has also been shown to have a detrimental impact on endurance, strength, and power (Cleary et al., 2006). The sometimes intense soreness can be attributed to changes in the sarcolemma or phospholipid membrane as a result of muscle microdamage (Cleary et al., 2006). It can be stated that if performance is the main training target that DOMS ought to be minimized to allow for enhanced feelings of recovery to drive improved performance in the future.

DOMS is known to be caused by eccentric loading of the muscle (Cleary et al., 2006). The combination of hypohydration and eccentric loading of the muscle has been theorized to lead to structural, contractile, and enzymatic protein denaturation as a result of reduced intracellular water (Cleary et al., 2006). The symptoms of DOMS from exercise is caused when the sarcolemma loses the ability to retain solutes such as potassium, creatine kinase, and myoglobin due to alterations on the cellular level. These solutes are released into the extracellular fluid, increasing the osmolarity of the extracellular fluid, driving water out of the cell. Potassium release is augmented with the increase in extracellular fluid, and counterintuitively increases the electrochemical gradient, making more water leave the cell.

Cleary et al. (2006) conducted a study to determine if hypohydration increases the occurrence of DOMS with 10 male students. DOMS was induced with a 45 minute downhill run in both the euhydrated and dehydrated groups after the dehydrated group was dehydrated using a heat chamber and fluid restriction while walking. The euhydrated group mimicked the protocol but without the heat and was allowed fluid consumption ad libitum. Both groups began the DOMS-inducing running protocol after core temperature returned to baseline after the walking. The dehydrated group reached a hypohydration level of 2.7% body weight loss before engaging in the downhill run. The results indicated that dehydrating individuals did not exacerbate the physiological effects of DOMS such as tenderness, ROM, or strength (Cleary et al., 2006).

Exercise Associated Muscle Cramps

Exercise associated muscle cramps (EAMC) are painful and involuntary contractions of skeletal muscle during or immediately after physical exercise (Schwellnus et al., 1997). Many conventionally believe that electrolyte and water depletion leads to EAMC. To investigate such claims, Martinez-Navarro et al. (2022) compared runners who experienced it and those that didn’t in a marathon with serum electrolytes, dehydration variables, and muscle damage serum markers. Ninety-eight marathoners were studied. Twenty of those, or 24%, developed EAMC. Body mass change, post-race urine specific gravity, serum sodium and potassium concentrations were not different between non-crampers and crampers. Runners with EAMC post-race didn’t show differences in hypohydration or electrolyte depletion after the race compared to those that didn’t experience EAMC, but exhibited significantly greater concentrations of muscle damage biomarkers, such as creatine kinase and lactate dehydrogenase. Similar patterns were shown 24 hours after the race. There was no sex difference in those that developed EAMC and those that did not. Pre-race creatine kinase and lactate dehydrogenase values were similar in both groups, demonstrating that the body responded during the race by producing higher levels of muscle damage biomarkers. What is of note is that history of injury and training volume since the last race were similar between the two groups. The authors posited that the way in which the athletes trained could be a large factor in the prevalence of EAMC. Approximately half of those who did not exhibit EAMC incorporated strength training in their regimen, while only 25% of those who exhibited EAMC strength trained. Potentially, those who developed EAMC during the race crossed their threshold of tolerance for exercise. However, the authors state that a factor that they did not include in their research is that some individuals may be predisposed to cramping. While hydration and electrolyte levels were not found to induce EAMC, training variety or predisposition had more of a factor (Martinez-Navarro et al., 2022).

On the contrary, Lau et al. (2019) found that water intake after dehydration makes muscles more susceptible to cramps, but that effect is reversed with the consumption of electrolytes. Ten men were studied, and hypohydrated by 2% of their total body mass. Muscle cramp susceptibility was assessed using electrical stimulation and how easily the subjects cramped in the calf muscle. Threshold frequency was measured before hypohydration, directly after, 30 minutes after, and 60 minutes after. Blood serum electrolyte measurements were taken before hypohydration, immediately after, and 80 minutes post hypohydration. The study was a crossover design, separated by a week with the subjects receiving spring water or electrolyte water with ingredients similar to that of an oral rehydration solution. Muscle cramp susceptibility didn’t change from baseline to immediately after downhill running for both spring water and electrolyte water. The average threshold frequency decreased after water intake 30 minutes and 60 minutes after ingestion, meaning that cramps were more easily induced. In contrast, the average threshold frequency increased after consumption of the electrolyte water. The threshold frequency was not changed when no fluids were consumed. Unsurprisingly, serum sodium and chloride concentrations decreased after water intake, but were maintained after electrolyte water intake. Various studies have shown how the threshold frequency of cramping with electrical stimulation isn’t altered between the two waters (Lau et al., 2019). The authors state that hyponatremia, where serum sodium concentration is less than 135 mmol /L, may be the cause of the results that contradict other research, as a typical symptom of hyponatremia is cramping. Thus, it is possible that water intake after dehydration dilutes electrolytes concentration in the body, inducing cramps. Lau et al. (2019) states that this may be the first study to demonstrate an oral rehydration solution reducing muscle cramps.

Glycogen

An important aspect in hydration and body weight is the presence of glycogen in the body. It is a crucial source of energy composed of carbohydrates. A certain amount of water is attached to a specific amount of glycogen in the body in muscle, liver and brain, as glycogen is very hydrophilic. Sudden weight gain or loss when first beginning dieting is usually a result of the gain or loss of glycogen along with the water attached to it. A common method of a temporary carbohydrate-heavy diet prior to a competition known as “carb-loading” utilizes the increase in glycogen, the main source of energy during short term exercise, as it is established that increasing glycogen levels increases endurance performance (Shiose et al., 2023).

The topic of hydration and glycogen levels has been around for well over a century. An estimation that 3g of water would accompany 1g of liver glycogen was made in early stages of research. Various studies using animals have shown that liver glycogen is associated with about a 1: 1.6-3.8 ratio with water. In regards to muscle, 1g of muscle glycogen is bound to 3-4g of water. (Shiose et al., 2023).

The science of muscle glycogen and water becomes tricky without muscle biopsy. This is because there is water in muscle that is not associated with glycogen. To investigate muscle glycogen resynthesis and muscle water content, a study was conducted where two drinks with identical carbohydrate content were consumed, with one drink having nearly eight times the volume (400 mL vs. ~3170 mL) (Shiose et al., 2023). The results showed a much higher ratio of change of glycogen to water with the more voluminous drink, likely due to an increase in non-glycogen bound water. Thus, muscle biopsy, while impractical, is the gold standard to understanding muscle glycogen and water content.

Another point of note is that hypohydration accelerates the use of glycogen compared to similar exercise intensities (Lopez-Torres et al., 2023). Insufficient rehydration after exercise decreases glycogen resynthesis, which can potentially have ramifications in the next bout of exercise. If proper fluid replacement is performed post exercise, glycogen restoration is more optimal. Even if enough carbohydrates are consumed, if the hydration is insufficient, glycogen replacement may be impaired, compromising performance.

Creatine

Creatine is a popular supplement for athletes and those who exercise to enhance performance, recovery, and muscle mass. It is a naturally occurring nutrient in red meat, and also synthesized within the liver. It is believed to enhance resynthesis of adenosine triphosphate. While the benefits of creatine are outside of the scope of this research, it is vital to understand if hydration is an important variable in supporting the positive effects of creatine. There are over 500 peer-reviewed publications on the topic of creatine supplementation showing its safety and efficacy, yet the supplement continues to be shrouded in mystery (Antonio et al., 2022). It is widely regarded in the athletic community that creatine supplementation should be accompanied with an adequate intake of water because creatine leads to water retention. However, this may be a slight misconception, as studies have shown that while creatine does in fact increase total body water and extracellular body water during the first several days of supplementation, the question remains whether or not this occurs over the long run. Creatine, like salt and sugar, is an osmotically active substance. It can be stated on a basic level that an ingestion of an osmotically active substance along with water will lead to an increase in body weight. Further, creatine is taken up into muscle cells through a sodium-dependent creatine transporter (Antonio et al., 2022). As a result of the involvement of sodium, there is an influx of water into the muscle cell to maintain regular osmolarity. However, based on sodium-potassium pump activity, this extra gain may be negligible (Antonio et al., 2022). Even so, studies involving exercise training and creatine supplementation have shown that there is not an increase in water retention in the body after consuming creatine for a prolonged period of time. While there is evidence of creatine supplementation increasing water retention, this is mainly short term, and there are many studies showing that its supplementation doesn't alter body water chronically.

It is also widely regarded that creatine causes dehydration or cramping. Experimental and clinical research doesn't support such claims. In fact, research has shown the opposite effect. In a study with 72 NCAA DI athletes divided into creatine supplementation and non-supplementation, the creatine users reported less cramping, muscle strains, dehydration, and total injuries (Greenwood et al., 2003).

Neurological Performance

There have been many studies on the effects of hypohydration on psychological and neurological factors. While it is apparent that severe hypohydration of levels of 5-8% of body weight incurs cognitive impairment, the question is where the threshold is for when cognitive impairments begin to occur (Wittbrodt and Millard-Stafford, 2018). Some have suggested that cognitive impairments occur in parallel with physical impairments, while others have said that they do not appear until 4% body mass loss.

Ely et al. published a study in 2012 regarding hypohydration and cognition, mood, and postural balance in multiple temperature environments, which was the first of its kind. The cognitive tests consisted of a psychomotor vigilance test, a reaction time test, a matching test, and a grammatical reasoning test. The mood states were determined through a questionnaire that included six mood subscales that combined to determine a singular mood score. Balance tests were performed on a Biodex Balance System. Participants were dehydrated to around 4% body mass loss, and if the levels went above that, they were rehydrated appropriately to reach around 4%. Participants were well trained, meaning that they were potentially better equipped for handling hypohydration versus untrained individuals.

The results of the experiment indicated that there was no interaction between hydration levels and skin temperature, as it increased linearly around 4°C for every 10°C increase in the environment (Ely et al., 2012). There was also no effect observed for reaction time or cognitive testing in any of the environments or hydration states. Thus, neither hypohydration of 4% or acute thermal stress were not enough to impair cognitive performance. This can be attributed to a phenomenon known as cognitive resilience in psychology, and other investigations support the minimal to no effect on cognitive performance with environment and hypohydration.

In contrast, a significant link between hypohydration and negative mood scores was found (Ely et al., 2012). Post hoc tests showed significantly increased mood disturbance in the participants while they were hypohydrated. Mood scores were 23% more negative while hypohydrated compared to when they were euhydrated. The subscores that were higher in value were anger/ hostility, confusion/ bewilderment, depression/ dejection, and fatigue. These were adversely affected by hypohydration but not the environment. In terms of balance, post hoc tests showed significant balance impairment at 10°C compared to all other environments. However, there were no meaningful differences in balance between the hypohydrated and euhydrated groups. The poor balance in a cold environment independent of hydration is supported by previous research. The authors hypothesized that balancing may be difficult due to low grade shivering. The involuntary muscular contractions add a greater degree of difficulty of stability on the Biodex Balance System. Another factor is when feet are severely cooled, mechanoreceptors become negatively affected, which can affect balance negatively.

Wittbrodt and Millard-Stafford published a meta-analysis in 2018 investigating 33 studies on the effect size of hypohydration on cognitive performance. Of the 33 studies, 27 only included males. Nine studies showed improvement in cognitive performance and 23 studies showed a negative effect. When combined, there was a slight overall favor towards impairment rather than improvement. Studies with hypohydration levels exceeding 2% showed greater decrements in cognitive performance than those that did not cross the 2% threshold. The findings showed that some cognitive domains such as attention, executive function, and motor coordination are more likely to degrade with hypohydration compared to lower-level tasks such as reaction time (Wittbrodt and Millard-Stafford, 2018). The specific mechanistic reasoning of the results is yet to be understood. The authors suggest that the aforementioned cognitive domains may activate different brain regions and neurotransmitter systems, making some regions more susceptible to cognitive impairment from hypohydration than others. Because hypohydration appears to degrade perceptual responses of sensory mechanisms such as thirst and hostility, it is possible that the thalamus and basal ganglia are the main regions affected for motor coordination (Wittbrodt and Millard-Stafford, 2018).

A factor which coincides with mood is perceived exertion. While heightened energy levels don’t always lead to improved performance in sport, it usually means increased strength and output. Weightlifters sniff ammonia to prepare for heavy loads and stimulate themselves to perform, while endurance runners listen to upbeat music. Clearly, a right state of mind, or mood, is necessary for athletes in performance settings. Athletes may report high exertion activities as "easy" in competition settings due to heightened focus and stimulation, which upbeat music will cause, for example. Thus, it can be reasoned that higher levels of stimulation and the right mood may lead to shifted levels of perceived exertion. Factors such as dehydration may impact mood and perceived exertion negatively, resulting in lowered performance. However,in the past, there has been conflicting evidence regarding the relationship between hypohydration and perceived exertion, with some studies saying that hypohydration increases it, while others state that it does not.

Rate of Perceived Exertion, or RPE, is a subjective measure that ranges from 6 to 20 developed by Gunnar Borg, and continues to be used in a variety of settings due to its ease of use. Deshayes et al. (2022) states that RPE may be considered the "mastermind" of exercise performance and adherence, because if an individual is to enjoy the activity, they likely will feel less strain when performing it, leading to better performance and adherence. It has also been suggested that RPE may act as a mediator of the effect of hypohydration on endurance performance. This would make sense considering how the effect of hypohydration on thermoregulatory, cardiovascular, and metabolic functions creates higher perceived strain on the body. While it is understood that the brain is the organ responsible for regulation of RPE, the exact mechanism is still debated. It has been shown that acute hypohydration does not alter brain volume, suggesting that the brain operates at near optimal levels despite the lack of water in the system.

Deshayes et al. (2022) published a systematic review to elucidate the impact of hypohydration (specifically exercise-induced hypohydration) on the rate of perceived exertion on endurance performance. There was much variation in the research findings in the analysis, which was to be expected with how varied the protocols were. Through meta-regressions, it was shown that in isolation, humidity, exercise duration, exercise intensity, aerobic capacity, and ambient temperature had little effect on RPE for each 1% of body mass loss. However, when all five variables were combined, they accounted for 66% of the variance among the changes in RPE. These confounding factors can make it difficult to elucidate the effect of other variables.

It is established that hypohydration increases heart rate, and such was observed in association with RPE. However, this is not groundbreaking, as the Gunnar Borg RPE model was initially created to mirror heart rate. The model that Deshayes et al. (2022) created indicates that for each increase in heart rate of 1 beat/min there should be an increase in RPE of .1 points for each 1% of body mass loss, which is very low. Even though statistically the change in RPE relates to hypohydration, the degree of practicality was negligible until a body mass loss of 3%. The insignificance of the results below 3% body mass loss makes sense because the difference between the hypohydrated group and euhydrated groups was less than 10 beats/min during exercise. An increase of 10 beats/min in heart rate with a 3% body mass loss would only equate to an increase in RPE of .3. However, the close relationship between heart rate and RPE is merely correlational, not causal, and should be taken with a grain of salt. Further, women only represented 1% of the total sample in the meta-analysis. The succeeding section will discuss a study by Gann et al. on the topic of RPE and muscular strength, endurance, and power in women.

Hydration and Marginalized Populations

Women

There is scarce research on the topic of women and hydration. All of the aforementioned studies in this work either completely or partially exclude women. While this may happen naturally in some research, women are purposefully avoided in many cases because of their hormonal variability in conjunction with the menstrual cycle. Even so, there is limited research on female sex hormones and their impact on dehydration. There are plenty of female athletes and active women, so it is of interest to understand how gender affects hydration and if there are differing protocols based on the individual.

In general, female reproductive hormonal profiles over the course of the menstrual cycle seem to have many implications on thermoregulatory and volume regulatory physiology (Giersch et al., 2020). Specifically, heat dissipation through cutaneous vasodilation is a large factor, allowing for efficient cooling of the body. This affects how much water is lost through sweat and how much water is retained in the body. The 28 day average menstrual cycle is also known to cause physiological changes in fluid loading, stress, exercise, sleep, mood, behavior, among other variables (Constantini et al., 2005). The effects and variables of the menstrual cycle are multifaceted and complex.

The menstrual cycle can be divided into four segments: menstruation, follicular phase, ovulatory phase, and luteinizing phase (Giersch et al., 2020). Menstruation can be considered part of the follicular phase and ovulation is a relatively short window of about 24 hours where the egg is released. In many studies, the cycle is largely divided into the follicular and luteinizing phase.

The hormonal profile of a menstruating individual contains the ebb and flow of many hormones. Estrogen, luteinizing hormone (LH), and follicle stimulating hormone (FSH) spike right before ovulation. While LH and FSH experience a very steep spike, estrogen is raised gradually throughout the follicular phase. After ovulation, progesterone and estrogen are the main hormones in circulation in the luteal phase.

Both progesterone and estrogen are associated with variation in body fluid regulation and may have independent impacts on hydration and fluid balance (Giersch et al., 2020). Progesterone and estrogen affect sodium regulation and hormones that are responsible for regulating sodium. Further, estrogen and progesterone influence changes in capillary fluid dynamics, affecting the fluid balance intra and extracellularly. Fluctuations in sex hormones during the menstrual cycle is linked to the release and activity of volume regulatory hormones like arginine vasopressin (AVP) as well (Giersch et al., 2020). Specifically, estrogen levels heighten AVP release (Giersch et al., 2020). Further, AVP release and thirst are stimulated by an increase in general blood osmolality, which is higher in general during various parts of the cycle.

During the luteal phase, there is a buildup of interstitial fluid during and an increase in the possibility of edema (Giersch et al., 2020). A favoring of interstitial fluid buildup may alter the osmotic balance in the body, causing a shift in body water compartments, lowering plasma osmolality. Thus, plasma osmolality is likely not a useful metric in studies involving women and hydration. The luteal phase specifically is also associated with an increase in aldosterone, which is a key hormone in the renin-angiotensin-aldosterone system. The luteal phase also may be more sensitive to AVP release and thirst sensation than the follicular phase. Thus, some researchers believe that women in the luteal phase have the potential to complicate study results. Further, it is also argued that the use of urine specific gravity (USG) may not be a valid choice of measurement either because women may experience acute increases in fluid ingestion leading to increased urine output due to the changes in hormonal profiles. However, Volpe et al. (2009) found that there was no difference between women in the follicular phase and women in the luteal phase in terms of hydration state, bringing into question the validity of discerning the two.

Giersch et al. (2022) states that menstrual cycle phase and dehydration could result in cumulative decrements in exercise performance. Similarly, women may be at a higher risk for heat illness when hypohydrated. Body temperature has been shown to increase ~.22 °C for every 1% loss in body mass during exercise in the heat. (Giersch et al., 2020). The competition for blood flow during exercise between cooling and exercise may limit heat dissipation through increased sweat rate and skin blood flow. Male studies have shown an exaggerated hyperthermic response when exercising in the heat hypohydrated (Giersch et al., 2020). During the luteal phase, a set-point shift occurs, increasing internal body temperature .3 - .5 °C in both rest and exercise (Giersch et al., 2020). However, there is currently no direct evidence to support the claim that women are at a higher risk for developing exertional heat illnesses over men.

Giersch et al. (2020) mentions how in 2014, 25.3% of those using contraception were using oral contraceptives, making it the most popular choice of birth control. There are many types and it is difficult to control variables on all of them. Oral contraceptives increase the levels of hormones that are produced during the menstrual cycle, potentially creating differing responses to hydration and hypohydration. The main finding in the effect of birth control on hydration is that it affects the production of AVP and lowers the threshold for thirst. Oral contraceptives, especially combination oral contraceptives which contain both estradiol and progesterone, are known to affect resting internal body temperature and alter blood flow to the skin during rest and exercise. Other forms of contraceptives are yet to be investigated in terms of hydration. Female reproductive hormones likely have a significant role in thirst and volume regulation in humans, which impact hydration status, responses to dehydration, exercise performance, and fluid needs. However, it is starkly apparent that much more research is needed on the topic of females and hydration.

There are few studies that solely focus on women, hypohydration, and exercise performance. Gann et al. (2020) conducted a study with a randomized, cross-over design to investigate the effects of hypohydration on women and muscular strength, endurance, and power with healthy female recreational weight lifters with a mean age of 22. The subjects began the study upon cessation of menses, completing all trials during the follicular phase of the menstrual cycle. Passive dehydration methods were used, where an overnight recovery period was implemented to allow the potential confounding effects of heat exposure to lessen. Subjects were dehydrated to 3% loss of body mass. The metrics used were one repetition maximum (1RM) bench press and 1RM leg press. To investigate muscular endurance, the same exercises were used, but with five sets with 75% of their 1RM to volitional fatigue. Vertical jump was measured by a jump height measurement system with the subjects performing countermovement jumps. RPE, perceived recovery status, and perceived readiness were measured using a 10 point scale.

Paired sample t-tests showed no significant differences between the hydrated (HT) and dehydrated (DT) trials for total body water. However, USG and hematocrit were higher for the dehydrated trial. While bench press 1RM was significantly lower for DT compared to HT, there was no significant difference found for leg press 1RM. There was also no difference in reps completed for bench press, leg press, or total volume lifted for both lifts. There was no significant difference in vertical jump height. No significant difference was found for heart rate after performing bench press and leg press, and the ratings of perceived exertion were not significantly different. Perceived recovery status was lower for DT, likely due to the subject's expectation of performance. Lastly, estimations of sleep quality were significantly lower for DT vs HT. The effects of hypohydration are not very apparent in this study besides the diminishment of 1RM bench press and ratings of perceived recovery status. While male studies can likely serve as a general guideline for females, more research is needed to fully understand the role gender may play in hydration.

The Elderly

There is a progressive decline of total body water and intracellular water with the process of aging (Lorenzo et al., 2019). In addition, the elderly population faces an elevated risk for low-grade chronic dehydration. Elderly individuals living in institutional care facilities are more likely to experience reduced fluid intake (Cook et al., 2019). While this is known to cause muscular performance determinants in the average individual, it could also affect an elderly individual's functional capacity. It has been suggested that a mere 1% of acute hypohydration in healthy active 60 to 75 year olds may negatively affect muscle performance (Serra-Prat et al., 2019). Other factors such as diseases or disabilities may hinder an individual's water intake. For example, elderly residents living with dementia are at high risk for dehydration (Hodgkinson et al., 2003). Decreased mobility, reduced functional capability, and impaired cognition are risk factors for dehydration and decreased fluid intake. As such, it can become a cycle of hydration loss if the issue is not addressed at the root, which is the lack of uptake of water.

The loss of intracellular water can be partially attributed to the loss of muscle mass with age. However, older adults lose thirst sensation and the ability to concentrate urine as well, which is likely a larger factor. This is further backed by how age-related muscle mass loss is only a small part of muscle weakening, meaning that muscle quality is of more importance than quantity (Lorenzo et al., 2019). Intracellular water, which determines cell volume, has been proposed as an indicator of muscle quality, and cell hydration has been linked to strength, function, and frailty. Prevalence of hypohydration in the elderly is estimated to be around 20% to 30% (Lorenzo et al., 2019). Hypohydration is associated with greater disability, morbidity, and mortality among the elderly (El-Sharkawy et al., 2015). There is a vast array of risks that Lorenzo et al. lists when it comes to hyperosmotic stress in the elderly. These include chronic inflammation, increase in reactive oxygen species and oxidative stress, diabetes, cardiovascular diseases, kidney disorders, and a general increase in risk of mortality (Lorenzo et al., 2019). It is also difficult to identify hypohydration in the elderly, but plasma osmolarity is the current gold standard in diagnosis.

In an observational cross-sectional study by Serra-Prat et al. (2019), 324 community-dwelling individuals over the age of 75 were recruited to be tested on lean mass (LM), muscle strength, functional performance, and frailty and their relationship to intracellular water (ICW). As expected, there was a negative correlation between age and the ratio of ICW and LM. There was also a difference in sex, where women on average had less ICW per kg of LM at 398 mL/kg as opposed to 417 mL/kg. The ICW/LM ratio was associated with the number of co-morbidities and number of medications a person was taking. The ICW/LM ratio for robust persons was 414 mL/kg, while it was 391 mL/kg for frail persons. All of the studied functional capacity parameters were associated with the ICW/LM ratio, indicating that a higher cellular hydration status to be a positive marker for health. However, causal relationships cannot be established due to the observational nature of the study.

Water exchange between extracellular and intracellular compartments is regulated by osmotic pressure, mediated by aquaporins. Extracellular water (ECW) osmolarity must remain between 285-295 mOsm/kg even with fluctuations in water and solute intake (Serra-Prat et al., 2019).

While there are general guidelines to water intake such as the “8x8” rule where drinking eight 8 oz glasses of water a day is encouraged, it is unclear as to what adequate intake for older people living with multiple morbidities is. It can likely be stated that in general, an ad libitum intake of water is less than ideal, especially for those with extensive health impediments or comorbidities. Some reasons for the higher risk of hypohydration is due to forgetting where to get drinks, refusing to drink, and choking and swallowing difficulties (Cook et al., 2019). Decreased mobility, reduced functional capability, and impaired cognitive function are also risk factors in dehydration and reduced fluid intake (Cook et al., 2019).

It is unlikely that a single intervention will be effective due to the many coexisting health problems in the elderly. Thus, a multi-component intervention strategy should be used. Some examples provided by Hodgkinson et al. (2003) include the use of specialized beakers, increased staff awareness on the importance of hydration, implementing feeding assistants, creating an improved atmosphere and environment design at meal times, a wider variety in beverage choice, and increased frequency of routine offers of beverages.

Haussinger et al. (1993) hypothesized that protein wasting in critically ill patients is at least partly due to decreased cellular hydration in skeletal muscle and liver. Thus, more attention should be paid to intracellular hydration rather than extracellular hydration. Ingestion of amino acids may help with increasing cellular hydration, working as a preventative measure against catabolic signals. Glutamine has been found to be the most potent for cellular swelling as well. Haussinger et al. (1993) suggests that glutamine dipeptides which are hydrolysed in circulation may be a valid solution to the inherent instability.

Practical Applications

Hydration protocols

General guidelines for hydration exist, such as the “8x8” rule or “1600mls for women and 2000mls for men” (Cook et al., 2019). European guidelines recommend 2.5 liters of fluid through food and drink for men, and 2 liters for women (Cook et al., 2019). Another guideline that accounts for body weight is 100mL/kg for the first 10kg, 50mL/kg for the next 10kg, and 15mL for the remaining kilograms (Cook et al., 2019). However, there is much variability in individuals in metabolism and activity level, with these protocols not always working for every person.

A cross-sectional study with NCAA DI athletes investigated the pre-practice hydration status in 138 males and 125 females (Volpe et al., 2009). Urine specific gravity was used as the means of assessment. The results indicated that 13% of student-athletes were significantly hypohydrated with a USG of 1.031 ± .002. 53% were in a moderately hypohydrated state with a USG of 1.024 ± .003. Only 34% were euhydrated, at 1.012 ± .005. 47% of men were hypohydrated compared to 28% of women. No difference was shown between the luteal and follicular phases of the menstrual cycles in women. Based on urinary studies, 40-50% of recreationally active individuals begin exercise in a light state of hypohydration (Deshayes et al., 2022). To attain optimal performance, hydration must be accounted for before, during, and after exercise.

When considering fluid hydration, there are three aspects to be discussed: volume, rate of ingestion, and composition of the fluid ingested (Evans et al, 2017). There needs to be a sufficient volume of fluid consumed for an euhydrated state to be achieved. This is especially important in athletes, as perspiration is a driver for hypohydration. It has been demonstrated that 150% to 200% of the water lost during exercise consumed within six hours is effective for recovery (Evans et al., 2017). Merely replacing the water lost during exercise is not sufficient for rehydration, as there continues to be a need for water after exercise ceases and recovery commences.

There is limited research on whether the rate of ingestion of fluid impacts the effectiveness of a rehydration protocol (Evans et al., 2017). A study found that consuming an isotonic sports drink in a volume of 150% of body mass loss resulted in higher cumulative urine volume when consumed over 30 minutes as opposed to 90 minutes (Archer and Shirreffs, 2001). This would suggest that more water is retained when consumed over a longer period of time. Similarly, Jones et al. found that rehydration was greater postexercise after 8 hours when 100% of fluid losses were consumed over 4 hours as opposed to 1 hour (Jones et al., 2010). Although an optimal rate of ingestion is subjective, it is apparent that fluid should be consumed at gradual pace when possible as opposed to large quantities at once.

Concerning fluid ingestion during exercise, some research has shown that drinking water ad libitum is not enough to maintain hydration during exercise (Greenleaf, 1992). This beckons the question if ad libitum intake is reasonable, as many athletes forget to hydrate during their sport, play a sport that allows for minimal time for rehydration, or play at an intensity that disallows sufficient fluid intake. As exercise intensity reaches levels of around 75% or above the individual’s VO2 max, the rate of which fluid can be processed and comfortably handled by the stomach and intestines and emptied into the bloodstream is decreased. Heightened intensity will likely decrease the amount of time the individual can focus on rehydration during exercise (Casa, 2004). In fact, many athletes only supply approximately 50% of sweat losses during exercise

(Logan-Sprenger et al., 2015) However, more research must be done, as a meta-analysis by Goulet and Hoffman (2019) found that programmed drinking and ad libitum drinking produced similar results in cycling and running performance. It is likely that starting exercise euhydrated and drinking ad libitum during exercise will not cause any health or performance detriments assuming rehydration is properly conducted post exercise.

For fluid composition, more solutes in a drink usually result in more fluid retention and reduced urine volume. The most important solute is sodium, as it is the most abundant cation in the extracellular fluid, having great influence on serum osmolality. It is also the most abundant cation in sweat, meaning that sodium levels must be replenished continuously, or else the extracellular fluid will become hypotonic, disallowing water to be retained in the body. As opposed to sodium, potassium is the main cation in the intracellular fluid, and only small amounts are lost in sweat. Only 4-8 mmol/L is lost compared to the 20-80 mmol/L for sodium (Evans et al, 2017). The loss of potassium is not as big of a concern as sodium, as most of it stays within the cell. However, the addition of potassium in hydration beverages may prove to be useful in balancing the osmolality gradient intracellularly and extracellularly.

Many individuals consume pure water throughout the day and during exercise. While this is the easiest and most cost-effective strategy in hydration, it may be suboptimal in certain circumstances. While perspiring heavily, there is a heightened need for effective hydration, as the rate at which water is lost is elevated. Moreover, the ingestion of pure water may lead to frequent urination due to the hypotonic nature of pure water compared to serum osmolality. continually drinking water without sodium may also contribute to hyponatremia. Consequently, the ingestion of certain solute-rich beverages may be advantageous in recovery after exercise. To prevent frequent water loss through urination and to potentially improve performance and recovery, a hydration strategy must be developed.

Hydration on a daily basis outside of physical activity is vital, as exercise typically occupies only a small part of even the most active people's lives. Individuals must be able to assess their hydration status on a daily basis. While total body water and plasma osmolality measures are the gold standard in doing so, these are not always the most practical metrics (Cheuvront and Sawka, 2006). Cheuvront and Sawka (2006) state that the best way to understand hydration levels on a daily basis is to use three metrics upon immediately waking to assess hydration status. The first is body mass changes. A change of over 1.1% in body mass may indicate dehydration or hyperhydration, though less likely. Body mass must be recorded over time in order to understand this metric better. The second is a conscious desire for water. If there is strong conscious thirst upon waking in the morning, it is likely indicative of hypohydration. Lastly, urine color may be used to assess hydration status. If urine is abnormally dark, it is likely that the individual is hypohydrated. If two of these metrics indicate hypohydration, it is likely that the individual must reconsider their fluid intake habits. If all three are present, it is very likely that the individual is hypohydrated. This model of body weight, urine color, and thirst is reflected in the WUT model created by Cheuvront and Sawka as seen in Figure 2 (2006).

Despite the fact that we eat food that contains water and other solutes beneficial to hydration, there is limited research on the coingestion of food and fluid. Maughan and Shirreffs (1996) compared two groups where one had a commercial sports drink while the other had flavored water and a solid meal. Water ingestion was exactly 150% of body mass loss during exercise for both trials. Fluid retention after the six hour recovery period was greater when plain water was ingested with the solid meal, likely from the higher electrolyte content. A study where a standard meal was consumed but the fluid ingested was different with one being plain water and the other containing 50 mmol/L sodium chloride found that fluid retention was greater with the sodium chloride drink (Miller et al., 2014). Evans et al. (2017) reported no difference in fluid retention between water and a sports drink when a meal was ingested during the rehydration period. More research is necessary, but plain water is likely sufficient in rehydration if a solid meal is consumed simultaneously. Hydration is particularly important before and during breakfast, and with medications for the elderly (Cook et al., 2019).

When considering physical activity, there are primarily three goals in terms of hydration: starting exercise in an euhydrated state, preventing hypohydration during the activity, and rehydrating following the activity to be ready for the next activity bout (Belval et al, 2019). Many research articles have shown that athletes start training in a hypohydrated state often (Evans et al., 2017). It is generally accepted that starting exercise in a hypohydrated condition will negatively impact performance, especially if in a hot or humid environment. An individual approach must be taken in hydration strategies, as the sweat rate varies among individuals. Most individuals sweat between one to two liters an hour, but it may be as high as three to four liters or more (James et al., 2019). The only way to truly understand an individual's fluid need is to measure sweat rate. This can be done by weighing oneself before and after exercise and calculating the amount of sweat lost per hour. No urination may occur during this period unless the urine volume is measured and accounted for in the final weight. If you lost more than 1% of your body weight during exercise, you drank too little. If you gained weight, you drank too much. (Cheuvront et al., 2006).

Beverages for performance

There are numerous selections when it comes to the type of beverage that one may consume for hydration. To better elucidate what beverages support hydration best and what protocol fits individual needs, it is essential to understand how beverages compare against one another. Maughan et al. developed the beverage hydration index in 2015 in a study involving 13 commonly consumed beverages. While large fluid deficits are uncommon in the general population during rest, knowledge of beverages that can maintain hydration status over a longer period of time may be useful where access to free water is limited or frequent urination is undesirable. In some sporting events, frequent hydration may not be possible, meaning that fluid must be retained for as long as possible. It was reasoned that a beverage hydration index may be developed similar to how the glycemic index defines the blood glucose regulation response to various foods. During the study, seventy-two fasted euhydrated male subjects were recruited. The subjects consumed 1 liter of a beverage over the course of 30 minutes. Urine output was measured over the subsequent four hours. The urine volume passed relative to water is calculated as the BHI of a beverage. After two hours, full-fat milk, skimmed milk, Oral Rehydration Solution (ORS), and orange juice had a higher BHI than still water. The authors reasoned that the water content of the beverages ranged from 88% to 100%, so the BHI was adjusted to standardize the water content. The final results indicated that drinks with positive sodium or potassium balances were typically those with the highest BHI. ORS had a positive sodium balance while orange juice and full fat and skimmed milk had positive potassium balances. The calculated BHI also showed that drinks with the highest macronutrient and electrolyte content were the most effective in maintaining fluid balance. Similarly, the authors stated that drinks with a high energy content regardless of macronutrient type will empty from the stomach more slowly than energy free drinks, resulting in a delay of the diuresis that follows.

The beverages studied in Maughan et al. included caffeine and alcohol, which are traditionally controversial substances when it comes to hydration. The diuretic effects of caffeine and alcohol result from the inhibition of arginine vasopressin (AVP) release. Two hundred and fifty to three hundred milligrams of caffeine is unlikely to cause any effect on urine output, but such an effect is likely when doses exceed 300 mg. The alcohol content of alcohol didn't increase diuresis over other drinks, but the alcohol may have canceled the hypothesized positive influence of energy density on BHI.

In 2021, Millard-Stafford et al. recreated the Maughan et al. (2015) study with different generic beverages, which included deionized water, an electrolyte beverage, a carbohydrate-electrolyte blend beverage, and a beverage with 2 g/L dipeptide (alanyl-glutamine) and electrolytes. The experimental protocol was identical to Maughan et al. (2015). However, urine and body mass was obtained on the hour instead of after the hydration period. After two hours, the electrolyte beverage and the carbohydrate-electrolyte blend beverage were the only two with positive net fluid balance. After four hours, BHI ultimately did not differ among the three non-water beverages. However, the electrolyte drink had the greatest net effect on BHI relative to water. In terms of urine osmolality, the amino acid beverage was the highest compared to the other three after four hours. The authors concluded that although the addition of electrolytes to beverages increased the BHI in the test subjects, the results were not statistically different from water. The addition of electrolytes does not significantly improve BHI index, but is more effective than the addition of macronutrients.

While the beverage hydration index gives a good general picture of how certain beverages hydrate, there is still an endless array of research on the topic of what beverages are superior in providing hydration. A meta-analysis by Rowlands et al. (2021) compared hypotonic, hypertonic, and isotonic drinks studied in the literature concerning research done on continuous exercise. The groups also included water and non-electrolyte drinks as well. The analysis revealed that hypotonic electrolyte drinks ingested during continuous exercise likely maintain better hydration than isotonic electrolyte drinks (Rowlands et al., 2021). Hypotonic electrolyte drinks were likely better than hypertonic electrolyte drinks and non electrolyte-drinks and water as well. Delta percent plasma volume (dPV) is the main metric used in this investigation, representing the change in central and circulatory body water volume. Even while adjusting for exercise intensity (metabolic rate), the buffering of the reduction in dPV was apparent with hypotonic drinks. The evidence is clear enough in this study that hypotonic solutions yielded the best hydration outcomes. This could be resulting from faster intestinal absorption in the proximal proximal intestine from the conditions favoring the uptake with a hypotonic solution.

It is of note that carbohydrates such as glucose drive osmotic pressure within the gut lumen (Rowlands et al., 2021). Glucose can facilitate water and sodium absorption across the intestine through cotransporter protein SLC5A1 (Peden et al., 2023). On average, for every 100 mOsmol 1/kg, dPV declined .3%. Higher carbohydrate concentrations present a negative correlation with water absorption in the small intestine. Sucrose as an MTC (multiple-transportable CHO) promotes greater solute and water flux compared to isocaloric glucose but is likely limited to situations where glucose concentration is above the maximal glucose transporter (SGLT1) saturation capacity. (Rowlands et al., 2021).

While electrolytes such as sodium allow increased body water retention, the exclusion of sodium from glucose solutions did not influence water absorption in the small intestine. This could be a result of the ability of sodium to freely cross the mucosa of the proximal intestine (Rowlands et al., 2021).

Protein ingestion is known to enhance post-exercise hydration. Gholizadeh et al. (2023) sought to elucidate whether the type of protein can alter such a response, namely between whey isolate and casein in a randomized controlled trial. Three drinks were concocted: A whey electrolyte blend with 22 g/L of whey, a casein electrolyte blend with 22 g/L of casein, and a purely electrolyte blend. All three drinks had a density of 66 g/L, with 44 g/L of electrolytes making up the remaining density in both protein blends. 30 male Iranian soldiers were recruited and were dehydrated to a total body weight loss of 2.2% running, which is about the standard for studies investigating hypohydration. The volume of water given to the subjects after the hypohydration was equivalent to 150% of the fluid loss. The results showed that the positive fluid balance was highest in the whey blend (.22L), next highest in the casein blend (.19L), and lowest in the electrolyte blend (.12L). The fluid retention was highest with the whey blend at 80.35%, casein at 78.65%, and electrolyte at 76.67%. A Cooper endurance capacity test was conducted after a three-hour rehydration period. The whey blend had the lowest time at 11.40 minutes, then electrolytes 12.9 minutes, casein 14.25 minutes. It was concluded that the inclusion of isolate whey protein in an electrolyte solution yields superior outcomes in rehydration. The whey isolate blend group had the lowest urine volume, heart rates, perceived thermal stress, and RPE. The authors stated that whey exhibits a more rapid digestion process and has a greater rate of absorption compared to casein. Whey is also better for enhancing bloodstream amino acids, which are effective for absorbing sodium and water.

Other studies have also shown efficacy in the addition of protein to beverages to aid in hydration. Seifert et al. (2006) showed that the addition of milk protein in a conventional sports beverage resulted in enhanced water retention, although the drinks did not match in calorie and electrolyte content like in Golizadeh et al. (2023). James et al. (2013) also demonstrated that the addition of milk protein to an electrolyte solution showed greater efficacy compared to an electrolyte solution with equal calorie and electrolyte content. Further, Li et al. (2015) produced the same result concluding that whey protein is better hydrating than casein protein.

A double-blind study by Peden et al. (2023) compared three drinks: a sugar free drink, a glucose-based drink, and an amino acid-based drink. The amino acid drink contained eight essential amino acids. The subjects were dehydrated by around 2.5% of their bodyweight and 125% of the fluid lost was given during the rehydration phase. Only the amino acid drink achieved positive sodium and chloride balance post-exercise.

The evidence suggesting that protein is beneficial for hydration beckons the idea that milk could be a potential hydration solution due to its electrolyte and carbohydrate content. However, the issue with milk is the high viscosity and energy density, which may lead to gastric discomfort if over ingested or ingested during exercise.

An interesting approach to ingesting enough electrolytes is through sea water. A systematic review by Aragon-Vela et al. (2022) investigated the efficacy of different forms of sea water on the hydration of human subjects. While the volume of research is limited and thus conclusions remain difficult to draw, it can be said that sea water seems to be more beneficial than regular water in enhancing recovery. This could be due to the high levels of magnesium and sodium, along with potassium and calcium. The trace levels of other elements such as selenium, chromium, zinc, and vanadium may have a role as well. What's worth noting is that magnesium plays a key role in the complex with ATP in mitochondria. According to Killileu and Ames (2008), magnesium deficient cultured human cells show mitochondrial dysfunction and may have weakened defenses to antioxidants. Multiple of the studies showed a consistent increase in interleukin-6 (IL-6), which has anti-inflammatory effects when induced by exercise. Exercise-induced IL-6 may upregulate glucose uptake and mitochondrial content in skeletal muscle through modulation of AMPK activity (Aragon-Vela et al., 2022). Sea water may also promote skeletal muscle's oxidative metabolism by exposing the muscle cells to IL-6 for a longer period of time. While the studies in the review support that sea water improves recovery speed and systemic inflammation, only four of the ten support the improvement of athletic performance, meaning that more research is needed.

Based on the concept that pH changes during high intensity exercise, it has been proposed that the supplementation of sodium citrate would offer a buffering effect on the body, potentially enhancing performance as opposed to the supplementation of sodium bicarbonate. Cerullo et al. (2020) found that sodium citrate enhanced fluid retention during exercise and increased plasma volumes. Another solution is alkaline water. According to Chycki et al. (2018), alkaline water may be an effective alternative to sodium bicarbonate in preventing exercise induced metabolic acidosis. In a trial with sixteen combat athletes over three weeks, it was found that alkalized water indeed enhances hydration, improves acid base balance and anaerobic exercise performance. The control group did not see any changes in results and the alkaline water group saw increases in upper limb average and peak power. There were also significant decreases in lactic acid concentrations at rest and increases post-exercise. There was a significant increase in blood pH at rest from 7.36 to 7.44, and an increase in bicarbonate both at rest and during exercise.

While there isn't a single answer, there are a variety of ways to achieve optimal hydration on an individual basis. What likely matters most is the volume and consistency of consumption rather than the type of beverage. Once an individual's sweat rate, exercise intensity, and sweat rate is understood, there is little more to be done. However, some may find particular drinks to be anecdotally helpful or others to be upsetting to their gastrointestinal system. As such, some experimentation on an individual basis is necessary. In general, water is likely sufficient for sedentary activities, and a little bit of sodium and carbohydrate as in a sports drink may be beneficial as in a sports drink during intense physical activity.

Conclusion

A slight decrease in performance may seem trivial for the general individual exercising for the sake of health and disease prevention. However, other factors such as recovery, perceived exertion, and decreased injury rates may be worthwhile reasons in attempting to maintain adequate hydration levels throughout the day. The lay person may benefit from a general hydration protocol such as the “8x8” rule if they are not sufficiently in a state of euhydration. A myriad of factors influence hydration status, and each individual should therefore approach it in their own way.

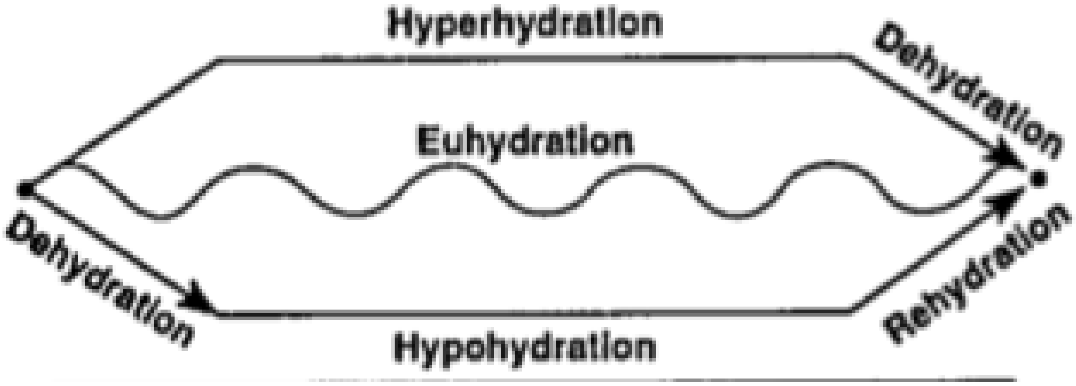
Slight decrements are important for the competing athlete, as a small margin may prove to be the difference between winning and losing in competition. Small negative performance effects in practice or training may accumulate over time as well, leading to suboptimal outcomes. Thus, it is highly important for the competing athlete to understand their hydration status. Starting exercise in a state of euhydration is likely a key factor in optimizing performance, especially for athletes who cannot regularly hydrate during their sport.

More research is needed in the realms of hydration and women and geriatric populations. The increase of general awareness of hydration status and variables that affect it may help to increase well-being and longevity.

Appendix

Figure 1

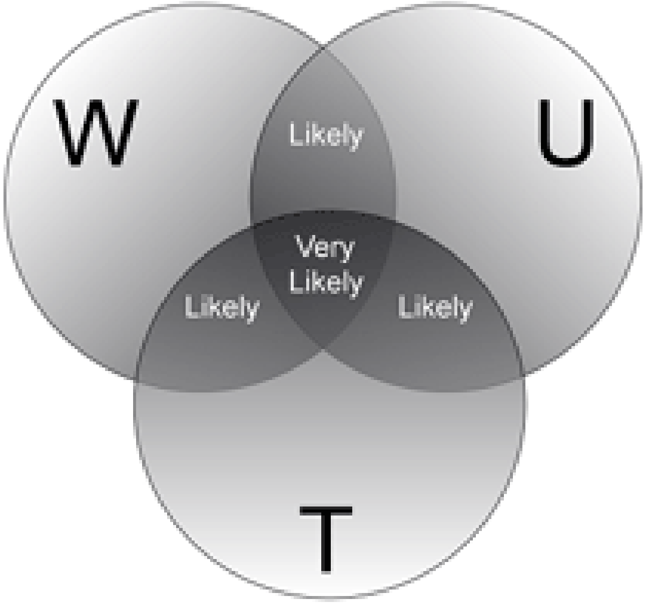
Body Hydration Terminology Diagram



Note. Adapted from Problem: Thirst, drinking behavior, and involuntary dehydration, by Greenleaf, J. E. (1992). *Medicine and Science in Sports and Exercise*

Figure 2

WUT Venn Diagram



Note. From Hydration assessment of athletes, by Cheuvront, S. N., & Sawka, M. N. (2006).

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