Effects of Water Consumption and Body Water Content on Exercise Performance in Recreational Athletes

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Abstract

Objective: To evaluate water consumption and body water content of recreational athletes to determine their effects on physical fitness and performance.

Methods: This secondary cross-sectional investigation utilized data from Drexel University. Participants had their data collected over two visits to the laboratory. Measurements taken in the original study included: aerobic fitness assessed via maximal oxygen consumption (VO_2max) using a metabolic cart, resting metabolic rate (RMR) evaluated using a metabolic cart, body composition measured by dual-energy X-ray absorptiometry (DXA), body water content measured by bioelectrical impedance analysis (BIA), kilocalories (kcals) from vigorous physical activity measured using Actical® accelerometers, water consumption assessed by asking participants how much water they consumed the day prior to each visit (at both time points), and dietary data from the 2005 Block Food Frequency Questionnaire (FFQ). R studio (RStudio 2023.12.1 Build 402 "Ocean Storm" for Windows, 2024, Posit Software, PBC, Boston, MA) was utilized to run linear models that fit all covariates (age, sex, body weight, height, body mass index [BMI], kcals from vigorous activity), water consumption obtained at time points 1 and 2, extracellular water [ECW], intracellular water [ICW], total body water [TWC] obtained by BIA at time point 1 only). These models analyzed the two-way interaction of VO_2max to the water variables or covariates. These models also analyzed three-way interactions of VO_2max to water variables and covariates combined. A stepwise linear regression was then used, and analysis of variance (ANOVA) tests were performed. Linear regression of the significant water variables was plotted showing variations in age and sex.

Results: A total of 141 individuals (65 females and 76 males), 18 to 64 years of age, were included in the secondary cross-sectional analyses. The youngest age group had the highest mean VO_2max and body water content (47.8 mL/kg/minute and 98.34 L (TWC), respectively). Changes in the covariates (age, height, BMI, kcals from vigorous activity) were each found to significantly affect VO_2max (all $P<0.001$). ECW ($P=0.0005$), ICW ($P=0.01$) and TCW ($P=0.016$) were significantly associated with VO_2max. Water consumption at both time points were not significantly associated with VO_2max. ECW had a strong positive relationship with VO_2max for those 18 to 29 and ≥50 years of age. There was an inverse relationship between ICW and VO_2max for those 18 to 29 years of age and those ≥50 years of age ($P=0.0020$ and $P= 0.59$, respectively). In those 18 to 29

years of age, as ICW increased VO2max increased, while for those ≥50 years of age, as ICW increased VO2max decreased.

Conclusion: There were no significant associations found between water consumption and VO_2max; however, significant correlations with water content assessed by BIA and VO_2max were found. The significant positive relationship among ECW, ICW and VO_2max, with variations by age, indicate that further research for these populations should be conducted because body water content may play a role in exercise performance.

Keywords: Adult athletes, Body water content, Exercise performance, Recreational athletes, VO_2max, Water consumption

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Introduction

Background

There is a universal understanding that water is vital for survival, and humans should consume adequate water to remain healthy. Except how does one know what amount of water is appropriate? Many numerical values have been recommended over the years; however, according to the National Academy of Medicine (formally known as the Institute of Medicine), the current recommendations for fluid intake in adults is 2.7 liters (L) per day for women and 3.7 liters per day for men [1]. This recommendation refers to total water consumption from food and other sources and not just water intake alone. Although these values have been established for fluid consumption, a consensus about the required amounts of water for human functioning of different demographic groups has not been established [2]. Armstrong et al. [2] noted in a review that water needs vary based on ambient temperature, physical activity, and age, and needs may change day to day, though internal responses to thirst is often sufficient enough to maintain appropriate hydration.

To understand individual water needs, it is important to determine water intake and body water content [1,3]. While there are several ways to assess water intake and body water content, some of the more common ways to evaluate these variables via dietary intake, hydration questionnaires for water intake and bioelectrical impedance

analysis (BIA) and urine osmolarity concentrations for body water content. Bioelectrical impedance analysis is conducted to determine the amount of body water content, fat mass, and lean body mass in the body. This is evaluated with sensors that detect electrical currents that pass through the body. The rate at which the current travels through the body helps to differentiate the tissue types (e.g., fat mass and lean body mass) [3]. Volpe and colleagues [4] stated that BIA is a fairly accurate method to evaluate body composition; however, it is not as accurate as other methodologies, such as dual-energy X-ray absorptiometry (DXA) or hydrostatic weighing. Urine osmolarity concentration provides information about the urine concentration; high urine osmolarity concentration represents concentrated urine, while low urine osmolarity concentration represents diluted urine [5]. Urine osmolarity concentration is tightly regulated. The physiological range is 50 to 1,200 mmol/kg or mOsmol/kg. Additionally, normal physiology should allow osmolarity concentrations to increase above 700 mOsmol/kg in response to dehydration, leading to secretion of arginine vasopressin and thirst response to prevent hypohydration or hypovolemia [6]. These are just a few of the tests used to understand the differences in water consumption and body water content. Understanding how water content is measured is key, though knowing the terms to describe water concentrations in the body is also important. When water content is within homeostatic concentrations this is referred to as euhydration. Dehydration is a measure of water lost from the. Water loss of more than 2% body mass is termed

hypohydration. Understanding these differences can help to differentiate meaning within the literature.

Water needs and average water consumption differ vastly between countries and cultures. For example, Guelinckx et al. [7] used population surveys from France and the United Kingdom (UK) to analyze the contribution of water from food to total water intake. Data were collected for just over 8,000 participants. The researchers reported that those from the UK tended to consume more fluids than those living in France. Furthermore, Laja Garcia et al. [8] evaluated 358 adults in Spain, by assessing water intake from hydration questionnaires and body water content from BIA. The researchers reported that women consumed significantly less water than men (1346.2 to 1497.2 mL/day vs 1449.0 to 1690.9 mL/day; P= 0.033). However, women who were underweight (BMI <18.5 kg/m^2) drank more water than men, though this was not significant (1099.2 to 1584.5 mL/day vs 914.8 to 1269.2 mL/day, respectively, P>0.05). Women with a healthy BMI (18.5 to 24.9 kg/m^2) women consumed less water than men (1348.2 to 1510.1 mL/day vs 1385.8 to 1635.2 mL/day respectively, P>0.05). Women who were overweight or obese (BMI ≥25 kg/m^2) consumed less water than men (1027.8 to 1869.9 mL/day vs 1491.5 to 2162.8 mL/day, respectively, P>0.05) [8]. Although the aforementioned water intakes were not significantly different, when adjusted for body weight, women had a significantly higher water consumption than men (P<0.05).

However, women consumed significantly less fluids than men when all forms of beverages were included, regardless of BMI category ($P<0.05$).

Women also obtained more water from food consumption and had higher body water content compared to men. Additionally, Ferreira-Pêgo et al. [9] assessed 16,276 adults across 13 countries on three different continents. Of the countries that participated, Japan had the lowest water consumption, while Germany had the highest water consumption (1.50 L/day vs 2.47 L/ day for Japan and Germany, respectively). These variations in water consumption were significant between country and sexes ($P<0.001$). When participants were assessed based on age, those between 18 to 29 years of age were most likely to meet recommendations than those 50 years of age and over, who were 12.4% less likely to meet recommendations (Odds Ratio [OR] = 0.88; 95% Confidence Interval [CI] = 0.80 to 0.96) [9]. These results indicate that water intake differs among countries and ages. Additionally, in 2018, the Centers for Disease Control and Prevention (CDC) reported that adults were consuming about 5.5 cups of water per day, with those ≥60 years of age only consuming about 4.5 cups of water daily [10,11]. With varying water intakes and a substantial portion of the population not meeting national recommendations, an investigation into how water intake affects exercise performance is needed.

Proper hydration is even more important in the active population. Body water is so tightly regulated that decreases can lower extracellular and intracellular water.

Decreases in extracellular water (ECW) directly effects blood volume, where less blood is available for the heart to pump and affected cardiac output, leading to less oxygen transported, causing a decrease in blood pressure and a decrease in energy production by the cells [12,13]. Both changes can negatively affect an athletes' performance. Due to this, many studies have been conducted to better understand hydration in athletes. Not only must athletes be concerned with the body's body water content, but also how their specific sport or climate might affect body water content and fluid intake. Yoshida and others [14] evaluated the body water content within Kendo athletes among different seasons. To assess body water content and how it was affected by energy expenditure, athletes were observed during practices. It was determined that body water content and sweat loss were seasonally dependent. Sweat loss in the summer was approximately 2.4 times more than that of winter (1,805 g vs 750 g; $P<0.001$). While water intake in the summer was also about 5 times that of the winter months (723 g vs 157 g; $P<0.001$) [14]. Water intake also varied by time of year. Because of this many athletes rely on internal cues and personal experience to determine their routine for hydration, though it is unknown whether this is more beneficial. Racinais et al. [15] evaluated hydration and performance in 83 marathon runners. Personal experience (91%) was the largest determinant in an athlete's drinking strategy compared to any other determinant ($P<0.001$) and was not affected by event type ($P>0.108$). Athletes did better and ranked higher in their race times when they relied on information from a "scientist" compared

to not relying on "scientists" (15 ± 12 vs 24 ± 13, respectively; P=0.013). Planned hydration volume, electrolyte intake, and carbohydrate intake all had no effect on performance in relation to finish time. Though, with recent researchers suggesting their benefit, an elevated number of athletes reported using either electrolytes (83%) or carbohydrates (81%) during the race [15]. These data, while valuable, leave some lingering questions about how athletes should hydrate and whether hydration, in fact, plays a role in their performance.

Performance in athletes can be correlated with several measurements. Maximal Oxygen consumption (VO_2max) is the maximum capacity of the body to uptake and utilize oxygen [16]. It is an excellent assessment of a person's cardiovascular and aerobic fitness. This test is typically conducted using indirect calorimetry using a treadmill or cycle ergometer. Various protocols are used to assess VO_2max (e.g., Taylor Protocol). Participants wear a mask connected to a metabolic cart, where oxygen consumption and carbon dioxide exhalation are measured. VO_2max is measured in Liters (L)/minute or milliliters (mL)/kilogram (kg)/minute (which is typically used because it is relative to a person's body weight). Xiang et al. [17] evaluated VO_2max by age among average adults. They reported that the typical VO_2max in those 21 to 30 years of age was 46.7 ± 11.5 mL/kg/minute, whereas it was 43.5 ± 11.3 mL/kg/minute in those 31 to 40 years of age. Xiang et al. [17] reported a VO_2max of 38.8 ± 9.3 mL/kg/minute in those 41 to 50

years of age, while those 50 years of age and older had a VO_2max of 36.8 ± 9.2 mL/kg/minute [18].

Though VO_2max has been determined with varying fitness levels and ages, there has been little research on how water intake and body water content may affect VO_2max. Nuccio et al. [18] determined that water loss of less than 2.5% of body mass had some effects on performance for various types of athletes. Hydration level was observed to affect cognition, performance skills, sprinting and anaerobic movements, like vertical jumps. Cognition appeared to be affected by lowering the athlete's vigilance, increasing time needed for decision-making, working-memory reaction, and reactive agility [18]. Performance skills were negatively affected across many sports and effected shooting performance, bowling and throwing. This effect seems most present at 2% to 4% water loss. Finally, anaerobic power seemed to be altered after 4% water loss [18]. Casa et al. [19] reported that dehydration had a potential negative effect on training and performance of athletes in track-and-field through fluid availability and sweat loss. This is typically considered a lower risk for non-endurance events, but those athletes who are in the longer duration events are at elevated risk and need to have individualized hydration practices. It has been well-established that fluid intake will help performance and can prevent adverse effects of dehydration; however, few researchers have assessed the direct effect of water consumption and body water content on VO_2max.

Problem Statement

Insufficient water consumption presents significant consequences to performance in athletes. Even mild levels of dehydration can lead to poor endurance performance, increased perceived effort, and increased fatigue [20]. During an athletic activity or sport, it can be estimated that as little as a 2% to 3% of loss of body water through sweat can affect performance [21]. Without proper hydration and rehydration, not only is there a decrease in performance, but an increased risk of adverse events, like heat exhaustion, heat stroke, and even death [22]. Therefore, fluid consumption during an event and throughout the day is important to maintain performance levels. The importance of hydration is not usually a focus for recreational athletes. Most researchers have evaluated athletes who are of college age and have not considered this effect in older athletes. There is a clear need to expand the knowledge of this age-related change in water intake and body water content. Without proper research in older athletes, there may be some application errors in the recommendations provided to older athletes and may put them at increased risk.

Purpose and Objective

The purpose of this study was to compare the water consumption and body water content of athletes among a wide range of ages to determine if hydration status affects physical fitness and performance. These parameters were evaluated through

previously collected data on: aerobic fitness via maximal oxygen consumption (VO_2max) using a metabolic cart, resting metabolic rate (RMR) evaluated using a metabolic cart, body composition via dual-energy X-ray absorptiometry (DXA), body water content using bioelectrical impedance analysis (BIA) to measure extracellular water (ECW), intracellular water (ICW), total body water (TWC), physical activity measured using Actical® accelerometers, water consumption assessed by asking participants how much water they consumed the day prior to each visit (at both time points), and dietary data from the 2005 Block Food Frequency Questionnaire (FFQ). The following specific aims and hypotheses were studied:

Specific Aims and Hypotheses

Specific Aim 1: To evaluate whether water consumption and body water content of recreational athletes, 18 to 64 years of age, is associated with maximal oxygen consumption (VO_2max).

Hypothesis 1: It is hypothesized that athletes who consume more water and have higher body water content will have a higher VO_2max, compared to those who consume less water and have a lower body water content.

Specific Aim 2: To differentiate the association of water consumption and body water content on maximal oxygen consumption (VO_2max) by age and sex in recreational athletes, 18 to 64 years of age.

Hypothesis 2: It is hypothesized that older athletes and women will consume more water and have a higher body water content compared to younger athletes and men [23].

Literature Review

Water Functions and Water Regulation

Water is often described as the 'Universal Solvent' because of its molecular properties. Polarity of water allows it to strongly attach to other polar molecules securely, especially itself. This property allows it to dissolve these polar molecules, hence the name [24]. That alone provides extensive uses within the body. Water helps the body by stabilizing cells, transportation across membranes, maintaining homeostatic temperatures, and assisting in circulatory and metabolic functions [2].

Because of all these valuable functions there is a tight regulation of body water content by the hypothalamus [25]. When water is lost through sweat, vomiting, uresis, etc., this depletion could come from extracellular or intracellular compartments in varying ratios that may not always be equal [26]. Extracellular fluid is highly affected, especially when sodium is lost, because it is the major solute of the extracellular compartment. These losses are regulated be many pathways in the body including thirst and hormonal responses. Water loss through uresis is regulated with the antidiuretic hormone arginine vasopressin, produced by the hypothalamus, and released by the posterior pituitary gland. Fluid osmolality, hypovolemia, and other system responses can cause secretion of this hormone [25]. High concentrations of arginine vasopressin

inhibit urine secretion. When insufficient water is available, the hormone is released to help retain water [27].

Johnson et al. [28] conducted a study that helped to illustrate these responses. They compared hormonal and thirst related maintenance of fluid balance in 120 women with varying water intake habits. During the first two days, participants consumed baseline fluids, followed by a required four-day decrease to 1.3 L/day or a four-day increase to 3.0 L/day to oppose their baseline consumption. Participants returned to baseline on the last day. Arginine vasopressin concentrations were significantly different in participants between baseline and the trials. The group who increased water intake had significant increases in arginine vasopressin concentrations (from about 1.25 to about 2.75 pg/mL) during the intervention. Arginine vasopressin concentrations returned to baseline post-intervention, however ($P<0.001$). The inverse was reported for the group that decreased water intake, with a significant decrease in arginine vasopressin concentrations (from about 2.75 to about 1.50 pg/mL) during the intervention. Arginine vasopressin concentrations returned to baseline post-intervention, however ($P<0.001$). Caldwell et al. [29] evaluated the effect of water intake on fluid hydration status in 23 participants over a 14-day period. The intervention group consumed 2.7 L (females) or 3.7 L (males) of water for the duration of the trial. These amounts correspond to the Adequate Intake established by the National Academy of Medicine. Caldwell et al. [29] reported a decrease in serum osmolarity

concentration (−438.7 ± 362.1 mOsm/kg) but an increase in urine volume (1,526 ± 869 mL) in the intervention group ($P<0.001$), with no significant differences found in the control group (serum osmolarity concentration: −74.7 ± 572 mOsm/kg; $P=0.45$; urine volume: −32 ± 1,376 mL; $P=0.89$). These results identified the relationship between water intake and hormonal responses. If water is limited to the body, a series of events typically occur. Blood volume decreases, and thus, heart rate must increase. This causes a lowering of stroke volume and the time available for filling the heart [30]. These compensatory actions are called cardiac drift. The counteraction of increasing heart rate by the body limits strain on the heart, and over time can become a concern [31]. Alternatively, when properly hydrated the body can function more efficiently. In a review paper, Çıtar Dazıroğlu & Acar Tek [32] reported that water consumption provides acute changes in the body and stimulates the sympathetic nervous system. This elevates the metabolic rate and, in turn, total energy expenditure through thermogenesis. On average, 500 mL of water consumption provides an additional 100 kiloJoules (kJ) increase in energy expenditure. Based on these findings water can help to improve energy production and help fuel the body for a day's work.

To further understand the effects of hydration status, a group of researchers wanted to assess water restriction and replenishment and the effect on body water content and with bioelectrical impedance analysis (BIA). Zhang et al. [33] recruited 76 adults in Baoding, China and randomized them into trial groups. All participants were

subjected to a 24-hour water restriction and with three meals with less than 75% water content. Group 1 received 1,000 mL of water, Group 2 received 500 mL of water, Group 3 received 200 mL of water, and Group 4 did not receive any water. Compared to baseline values, Zhang et al. [33] found an increase in the intracellular water (ICW) to total body water (TBW) ratio (ICW/TBW), but a decrease in extracellular water (ECW), and TBW in all participants after the 24-hour restriction ($P<0.05$ for all comparisons). During rehydration, Groups 1 and 2 had significantly higher ICW than Group 4 ($P=0.031$). Only Group 1 was significantly higher in TBW compared to Group 4 ($P=0.047$). When baseline to rehydration groups were compared, Group 1 returned to their ICW and TBW hydration status, while Groups 2, 3 and 4 significantly decreased ICW, even after rehydration testing ($P=0.037$, $P=0.004$, and $P<0.001$, respectively) and TBW ($P=0.047$, $P=0.003$, and $P<0.001$, respectively). Based on these findings, ICW and TBW both required significant water consumption to return to baseline hydration status and require regular consumption to be maintained. Additionally, the body's hormonal responses allow for adjustments to the lack of water, but this does not necessarily prepare the dehydrated body for exercise.

Early Research on Hydration and Performance

The relationship between hydration and performance seems to be well-established among the athletic community [18]. Proper hydration is vitally important

for a healthy body; especially during exercise; however, it is crucial to further investigate the current research regarding hydration for performance. Research associated with water consumption and performance has been conducted for decades and many valuable studies have produced key information still applicable.

Maughan et al. [34] researched the association between exercise intensity and its effect on fluid absorption. They included six male volunteers, 34 ± 3 years of age, who performed a series of VO_2max tests via a cycle ergometer. A baseline resting trial and three exercise trials were conducted at 42%, 61%, or 80% of VO_2max. For the exercise trial, participant's hands were placed in gloves while cycling. During the resting trial, their hands were in water. All participants ingested 200 mL of a glucose-electrolyte solution before each trial. Blood samples were then taken prior to ingestion, and at 2, 4, 6, 8, 10, 15, 20, 25, and 30 minutes after ingestion. Oxygen consumption by indirect calorimetry was measured at 20 and 40 minutes during each trial. Absorption of water by the body was slower in the two higher intensity exercise trials with 80% VO_2max ($P<0.05$). The amount of time needed to reach maximum water uptake in the body was significantly longer during the two higher intensity exercises compared with rest ($P<0.02$) [34]. Based on these findings, it is clear the absorption of water during exercise is influenced by intensity, implying the importance of proper hydration prior to exercise.

Heart rate and other body measures can also be affected by the level of hydration. To further understand this, Southard and Pugh [35] investigated 15 males enrolled in the United States (US) Air Force Academy on the effect of hydration on VO_2max estimates using heart rate. Each participant was subjected to a submaximal cycle ergometer test, two separate times within three days. The first test was after a fluid restriction of 12 hours, and the other test was after a hydration session in which they were required to consume water at 2% of their respective body weights 10 hours before the test, and 1% of their body weight 30 minutes before the test. Maximal oxygen consumption was significantly lower during the dehydrated trials than the hydrated trials ($P<0.01$) [35]. The results of this study show a clear picture that supports the relationship between hydration and the body's ability to perform exercise.

Kenefick et al. [36] assessed the effects of hypohydration on the lactate threshold in six female and eight male collegiate athletes. Lactate threshold is a key determinant of physiological fitness because untrained athletes accumulate a much higher rate of lactate than trained athletes at a submaximal intensity [37]. Each participant underwent two separate treadmill sessions until they reached exhaustion under either euhydration or hypohydration of about 4% of their body weight. The lactate threshold did appear earlier during exercise and at a lower rate of perceived exertion (RPE), respiratory exchange ratio (RER), and oxygen consumption when hypohydrated ($P<0.05$) compared to euhydration. Lactate concentrations are a direct result of increased glucose

metabolism during exercise and mark the onset of oxygen depletion to the muscles [37]. Based on Kenefick et al.'s [36] results, it can be interpreted that the lactate threshold appeared to occur much earlier and at a lower oxygen consumption than during euhydration, thus limiting performance by increasing muscle fatigue earlier.

González-Alonso et al. [38] investigated how exercise can be affected by hydration and environmental factors. They hypothesized that a lowered stroke volume due to heat stress would increase blood flow to the skin, and affect other factors associated with stroke volume. Eight male participants were selected for a trial comprised of cycling for two hours in the heat. Following this, participants rested for 45 minutes, then cycled for 30 minutes under hot or cold temperatures (35 degrees Celsius or 8 degrees Celsius, respectively), with 45 minutes of rest between the two trials. This was conducted on four separate occasions, while being euhydrated or dehydrated at 1.5%, 3.0%, or 4.2% of their body weight. Stroke volume declined by 6.4 ± 1.3 mL (4.8%) with every 1% of body weight lost under heated conditions. González-Alonso et al. [38] also reported an association between a reduced stroke volume, elevated heart rate, and decreased blood volume under both environmental conditions (Heat: $R=0.96$, $P<0.01$; Cold: $R=0.85$, $P<0.01$). However, decreases in stroke volume were not associated with increases in skin blood flow. These changes related to hypohydration are likely due to lower blood volume and negatively affected stroke volume, and subsequently, cardiac output, leading to a decreased capacity for exercise performance.

Over time, more emphasis has been placed on understanding the environment and heat related factors to hydration and performance. To further evaluate this, Lynn et al. [39] evaluated the relationship between fluid replacement and heat stressing environments, and how they affect performance and cardiac functioning. The researchers included 14 adult males trained in endurance exercise, who were assessed under three different conditions: no water consumption during exercise in a neutral environment, water consumed to match sweat loss in a neutral environment (hydrated), or no water consumption in a hot environment, during 60 minutes of cycling at 60% of VO_2max. During the trial, arterial pressure, cardiac output, and heart rate were measured with a 5-lead echocardiogram throughout exercise trials. Heart rate was lower after 30 minutes of exercise and continued to be lower post-exercise under hydrated and under-hydrated neutral environmental conditions compared to heated under-hydrated conditions ($P<0.05$). Cardiac output was not reduced at any point during either the hydration or the heated trial ($P>0.05$). During the hydrated neutral and the under-hydrated heated trials, the participants had cardiac outputs that were higher than the under-hydrated control condition in a neutral environment by 0.414 l L/minute and 0.392 L/minute, respectively during recovery ($P=0.017$). These results indicate a relationship between hydration and elevated cardiac output during exercise and recovery. Because the researchers did not evaluate hydration in heated conditions, it is difficult to evaluate the effect of hydration on performance in hot environments.

These investigations laid the foundation to establish how hydration may affect the ability to reach maximal performance. This established a clear understanding that proper hydration, especially prior to exercise, can improve VO_2max, cardiac output and lactate thresholds, which in turn, can improve exercise performance.

Athletes and Hydration

Early research clearly suggests a possible involvement of water intake on exercise performance, though many researchers have continued to evaluate these parameters in more recent years. Wang et al. [40] assessed the relationship between water intake, biomarkers for hydration, and physical activity in young male athletes. Wang et al. [40] conducted a cross-sectional study including 42 male athletes from Beijing, China, 18 to 25 years of age [40]. Each participant's total drinking fluid was evaluated with seven days of 24-hour fluid intake questionnaire. If any drinks were associated with an activity, descriptions of the activity were required. Wang et al. [40] reported that the median total water intake was 2,771 mL per day, with only 45.2% of the participants who met the recommendations for water intake in adult males. For total drinking fluids, the median value was 1,653 mL per day, while median water intake from food was 1,088 mL/day. Total drinking fluid recommendations were only met by 50% of the participants. Participants were also separated into 4 metabolic equivalent (MET) level groups. The MET groups were separated into four groups: Group 1 (1.08 to 1.30 METs),

Group 2 (1.31 to 1.40 METs), Group 3 (1.44 to 1.60 METs), and Group 4 (1.62 to 1.84 METs). Among all MET groups, significant differences were reported for intakes of total water and total drinking fluid (x^2=11.787, P=0.008; x^2 =11.658, P=0.009). Group 1 (2,532 mL) had significantly lower total water intake compared to Group 2 (3,305 mL) and Group 4 (3,282 mL) (P<0.05 for all comparisons). Wang et al. [40] reported a significant increase in total water intake (Group 1: 2,413 mL, Group 2: 2,599 mL, Group 3: 3,019 mL, Group 4: 3,421 mL; Z=2.414, P=0.016 for all comparisons) and total drinking fluid (Group 1: 1,422 mL, Group 2: 1,681 mL, Group 3: 1,602 mL, Group 4: 2,109 mL; Z=2.425, P=0.015 for all comparisons) with elevated energy expenditure from physical activity. Plasma cortisol concentrations in the Group 1 (73.50 ng/mL) were significantly lower than Groups 2 or 4 (94.21 ng/mL or 97.08 ng/mL, respectively; P<0.05). These researchers helped to identify the need for increased water consumption during intense exercise bouts to maintain hydration, and the lack of proper hydration found among male athletes.

Juett et al. [41] investigated the effects of under-hydration in male athletes who exercised at a high intensity. They conducted a randomized, cross-over design which consisted of 14 male participants, who were physically active in sports or running. Participants completed six sessions of 15-minute shuttle runs under temperate conditions, both under euhydration and dehydration conditions, separated by a seven-day washout. While running, they were provided either with enough water to consume

the equivalent to 90% of their sweat loss, or only 75 mL of water (hypohydration). During hypohydration trials, serum osmolality and urine osmolality were significantly increased compared to the euhydrated trial ($P<0.001$ and $P=0.024$, respectively). Furthermore, plasma volume was lower in the hypohydration trial compared to the euhydration trial ($P=0.002$). Sweat loss was not affected by trial type ($P=0.932$). Body mass loss was more prominent in the hypohydration trial compared to the euhydration trial (-1.6 ± 0.23 kg vs -0.17 ± 0.22 kg, respectively; $P<0.001$). Heart rate was significantly increased during hypohydration, with an average of 149 ± 12 beats per minute (bpm) compared to euhydration (143 ± 13 bpm) ($P=0.004$). During the recovery period, water intake was much higher after the hypohydration trial compared to the euhydration trial (2,997 ± 843 grams [g] vs 2,348 ± 1166 g, respectively; $P=0.01$). High intensity exercise appears to cause cardiovascular strain, though adequate hydration seems to lower these effects on heart rate and body mass loss, likely allowing the body to perform better and for longer periods of time.

Kuswari et al. [42] conducted a cross-sectional study in 32 ice hockey players (13 females and 19 males) who were assessed for the effect of energy, protein, and fluid intake and physical activity with VO_2max. They reported a significant association with fluid intake and physical activity and VO_2max ($r=0.55$, $P=0.001$ and $r=0.40$, $P=0.02$, respectively). Before exercise, hydration status was significant compared to VO_2max ($r=0.51$, $P=0.001$), though after exercise, hydration status was not significant ($r=-0.05$,

P=0.77). Based on Kuswari et al.'s [42] research, proper water intake prior to exercise has a positive effect on performance, while hydration after a workout is much less important for performance.

Adams et al. [43] conducted a study on hypohydration and performance in 11 male cyclists. Participants performed three individual 20-minute sessions of cycling at 50% of their peak oxygen consumption followed by a 5-kilometer (km) time trial at 3% grade. Participants were provided 25 mL of water in 5-minute intervals during the 20-minute sessions, and at 1-km during the 5-km time trials. This experiment was conducted twice, on separate days. In both trials, participants exercised in dry heat conditions in either a euhydrated or hypohydrated state. During euhydration, participants were infused with saline to allow sweat to be fully replaced by an intravenous (IV) saline solution. During hypohydration, participants were infused with a placebo IV solution. Plasma volume in the euhydrated trial was significantly higher than in the hypohydrated trial (after three bouts: euhydrated: 2.5 ± 5.7% vs hypohydrated: −9.8 ± 8.1%; $P<0.05$). However, serum osmolality increased in both trials (after three bouts; euhydrated: 304 ± 6 mmol/kg vs hypohydrated: 302 ± 7 mmol/kg; $P>0.05$). Nine of the 11 participants performed better in the euhydrated time trial than in the hypohydrated trial time trial. Mean power during the initial trial was not significantly different between the euhydrated and hypohydrated trials (306 ± 52 Watts vs 297 ± 53 Watts, respectively; P=0.06). During the second- and third- time trials, the

euhydrated group had significantly higher power compared to the hypohydrated group (309 ± 52 vs 306 ± 55 Watts [second time trial], 287 ± 49 Watts and 276 ± 54 Watts [third time trial], respectively; $P<0.01$ for both trials). Core temperature was also found to be higher in the hypohydrated group compared to the euhydrated group during the trials. These data indicate that hypohydration resulted in an increased strain on the thermoregulation and hydration status of the body, while euhydration maintained a homeostatic state, thus allowing for a more ideal performance level.

Costa et al. [44] investigated the gastrointestinal effects that are often associated with dehydration. Their randomized control, cross-over design study consisted of 11 male endurance runners who performed a two-hour running session at 70% of VO_2max. All participants completed these trials twice under hydrated and dehydrated conditions, with a separation period of one week. Heart rate, ratings of perceived exertion, and gastrointestinal symptoms were collected every 15 minutes during the trials. Breath samples were collected every hour during the trial and every half hour during the first three hours of recovery. Heart rate and ratings of perceived exertion both had significant trial x time interactions ($P=0.038$ and $P=0.001$, respectively), suggesting that the groups responded differently over time.

With respect to gastrointestinal markers, the researcher reported that high intestinal fatty acid binding protein (I-FABP) concentrations were significantly greater during the hypohydration trials compared with the euhydration trials ($P=0.047$). Fecal

calprotectin concentration did not appear to be affected by trial types. A trial time interaction was observed for breath hydrogen concentrations (P=0.034). Significantly higher breath hydrogen concentrations were found in the hypohydration trials starting at 1.5 hours in recovery (about 7 parts per million [ppm], P<0.001) and continued to be significant compared to baseline (>10 ppm, P<0.001). Additionally, the hypohydration trial was significantly higher than the euhydrated trial at 2 and 2.5 hours (P<0.01 for both trials). The results of this study further support the notion that hypohydration negatively affects physiological function, while hydrating properly can limit these effects. More specifically, higher instances of gastrointestinal symptoms, and I-FABP concentrations, breath hydrogen concentrations are all bodily responses to this excess strain. These symptoms were far less present in those who were properly hydrated.

The research on hydration and performance has primarily been conducted in young men, though it is important to understand this relationship for both sexes. To better understand hydration effects on athletes based on sex, Ramos-Jiménez et al. [45] conducted a study in 21 athletes (9 females, 24.1 ± 4.5 years of age; 12 males, 30.0 ± 6.2 years of age) in spinning sports. Individuals were randomly assigned to one of three hydration protocols (no fluid, plain water, or sports drinks) during a 90-minute spin session. Women in the no fluid trial had less body mass loss than men in the no fluid trial (-1.21 ± 0.72 kg vs -1.69 ± 0.68 kg, respectively), though this was not significant. Women also needed smaller amounts of fluid to maintain hydration compared to men.

For body temperature, the results were as follows: women: no fluid: 36.9 ± 0.3 degrees Celsius, plain water: 36.7 ± 0.5 degrees Celsius ($P<0.01$ compared to no water), sports drink: women: 36.7 ± 0.3 degrees Celsius ($P<0.01$ compared to no water); men: no fluid: 37.3 ± 0.5 degrees Celsius ($P>0.01$ compared to women), plain water: 36.9 ± 0.3 degrees Celsius ($P<0.01$ compared to no water; $P>0.01$ compared to women), sports drink: 37.0 ± 0.4 degrees Celsius ($P<0.01$ compared to no water; $P>0.01$ compared to women) [45]. For blood pressure, the results were as follows: no fluid: women: 94 ± 5 mmHg vs men: 114 ± 8 mmHg; plain water: women: 91 ± 4 mmHg vs men: 112 ± 10 mmHg; sports drink: women: 88 ± 6 mmHg vs men: 111 ± 7 mmHg ($P<0.01$ for all comparisons). For heart rate, the results were as follows: no fluid: women: 154 ± 16 bpm vs men: 147 ± 12 bpm; plain water: women: 145 ± 19 bpm vs men: 141 ± 14 bpm; sports drink: women: 145 ± 17 bpm vs men: 142 ± 16 bpm ($P<0.01$ for all comparisons) [45]. Consistent with previous studies, these results indicate that proper hydration can prevent strain on the body due to increasing temperature, blood pressure and heart rate with dehydration during exercise.

Volpe et al. [23] examined the pre-exercise hydration status of collegiate athletes and any factors that may influence hydration. They included 125 female and 138 male athletes of various sports (19.9 ± 1.3 years of age). This cross-sectional design included collection of one spontaneously voided urine sample. Each sample was then measured twice for urine specific gravity. Fluid intake was collected for all participants via a fluid

intake questionnaire. Menstrual cycle information was collected for all women from the same questionnaire. Based on urine specific gravity, participants were placed into one of three hydration status groups: euhydrated: urine specific gravity <1.020, hypohydrated: urine specific gravity between 1.020 and 1.029, significantly hypohydrated: ≥1.030 [19]. Among the three groups defined, only 34% of the collegiate athletes were found to be euhydrated ($P<0.05$). Although, women tended to be more euhydrated (28% hypohydrated) than men (47% hypohydrated). Women consumed more water (1,590 mL) than men (1,530 mL) ($P<0.05$). Women (3,060 mL), however, consumed less fluids than men (3,810 mL) when all beverages were combined. Additionally, there were no significant differences in fluid intake between menstrual phases (luteal and follicular phases, $P>0.05$). Time of day for testing did not appear to have a significant effect on hydration status among athletes.

Hydration Sources

Hydration can be maintained by a variety of fluid sources. Any form of fluid, whether from foods, like soup or fruit, or from liquids, like coffee or milk, is accounted for in hydration status and can support body water content. Maughan et al. [46] assessed the effects of 13 types of drinks on urine output and fluid balance in 72 well-hydrated men. The drinks included were sparkling water, Coca-Cola®, Diet Coke®, Powerade®, oral rehydration solution, orange juice, lager beer, hot black coffee, hot

black tea, cold black tea, full-fat milk (3.6% fat), or skim milk. The researchers reported that full-fat milk, skim milk, and the oral rehydration solution all had a significantly large effect in lowering urine mass and increasing fluid balance across the four hours after consuming one liter of liquid compared to water. Water had a cumulative urine output of about 550 g, whereas full-fat milk, skim milk, and the oral rehydration had cumulative oral outputs of about 294 g, 339 g, and 362 g, respectively ($P<0.05$ for all comparisons).

Similar to full-fat milk, skim milk and the oral rehydration solution, orange juice had a significantly lower urine mass and increased fluid balance in the first three hours after consumption ($P<0.05$), but was not significantly different from water at four hours ($P>0.05$). This helps to illustrate that some drinks may be more effective than water for adequate hydration.

Botek et al. [47] evaluated the effects of hydrogen-rich water on weight training performance. Hydrogen-rich water is created in a laboratory by dissolving hydrogen into water under high pressure. Hydrogen-rich water is an antioxidant, anti-inflammatory, and anti-apoptotic solution that can help to reduce oxidative stress [48]. Hydrogen-rich water showed a potential benefit with minimal negative effects to health, and may even enhance performance and associated recovery. However, hydrogen-rich water is still a novel concept and further examination is needed.

Botek et al. [47] conducted a randomized, double-blind, placebo-controlled cross-over study with 12 male participants [47] who were assigned to either the hydrogen-rich water group or the placebo group. Participants performed one set of six to eight repetitions of resistance training at 50% of 1-reptition maximum (1-RM) for half-squats, knee flexion, and extension drills, with one minute recovery between sets. Then each participant completed three sets of 10 repetitions of the same resistance drills at 70% of 1-RM. They finished the session with lunges at 30% of their body mass for three sets of 20 repetitions. Botek et al. [47] reported that those in the hydrogen-rich trial were able to perform lunges at a faster rate compared to the placebo ($P<0.001$). Serum lactate concentrations, measured midway and immediately after the trials, were significantly decreased in the hydrogen-rich water trials compared to the placebo (5.3 ± 2.1 and 5.1±2.2 [midway measurement], 6.5 ± 1.8 and 6.3 ± 2.2 mmol/L [immediately after exercise measurement], respectively; $P<0.008$ for both comparisons). Based on these data, it appears that short-term hydration with hydrogen-rich water improves resistance training, while limiting fatigue and muscle soreness caused by increased lactate concentrations.

Porto et al. [49] conducted a study on energy drinks versus water on aerobic exercise compared in 29 healthy males, 24.4 ± 2.8 years of age. In their randomized, controlled, cross-over design, all participants were subjected to three different trials at separate times. They conducted a baseline trial for determining VO_2max in which

participants completed the test with and without energy drink consumption. The experimental trial consisted of each participant drinking 200 mL of a standardized energy drink followed by 30 minutes of treadmill running at a 1% incline at 60% of VO_2max. At the end of this trial, participants lied supine for 60 minutes of recovery. In the placebo trial, participants performed the same protocol, only with water. The researchers reported that, after five minutes of recovery, the water group (placebo) had significant decreases in heart rate variability that remained decreased at 30 minutes, 6 hours, and 24 hours of recovery compared to baseline ($P=0.05$). The energy drink group did not have significant reductions in heart rate variability when evaluated by the standard deviation of all normal heart rate variability. However, when analyzed with the square root of the mean square of differences, Porto et al. [49] reported a significant difference in heart rate variability for the placebo group and energy drink group at five minutes recovery ($P<0.001$ for both groups) and 10 minutes recovery ($P<0.05$ for both groups) compared to baseline.

García-Berger et al. [50] conducted a randomized, cross-over study to evaluate the difference of skim milk versus sports drinks on exercise performance in nine cyclists, 26.8 ± 4.8 years of age. A hydration protocol was completed by each cyclist before cycling in an 18.6-km time trial race. Participants either consumed skim milk or a sport drink in 350 mL doses at three hours and 1.5 hours before the 18.6-km time trial. After the race, there were significant increases in urine color and urine specific gravity

for all participants from baseline (P=0.04 and P=0.01, respectively); however, no significant variation in these hydration status markers were observed between skim milk and the sports drink (P>0.50). Body mass significantly decreased with consumption of both skim milk and the sports drink after the race compared to baseline (body mass loss for both groups: 2.1 ± 0.48%; P<0.0001). Although both groups lost the same percentage of body mass, there were no differences in exercise performance observed between skim milk and the sports drink (P=0.89). Water consumption during the time trial did not vary between skim milk and the sports drink (P=0.55 and P=0.84, respectively). García-Berger et al. [50] reported no differences in drinking skim milk or sport drinks in time trial performance. Thus, hydration with added micronutrients may be valuable during exercise regardless of type. Skim milk could be a viable option for those with differing preferences in need of adequate hydration for exercise.

Castro-Sepulveda et al. [51] evaluated the effects of pre-workout water, beer, or non-alcoholic beer on exercise in athletes. The researchers implemented a double-blind, randomized, controlled study that consisted of seven professional male soccer players in Chile, 19.1 ± 0.4 years of age. All athletes were subjected to three trials in which they ingested 0.7 L of water, beer, or non-alcoholic beer, 45 minutes before performing a 45-minute treadmill test at 65% of their maximum heart rate. Urine specific gravity was significantly decreased from baseline for water and non-alcoholic beer (-0.9% g/mL and -1.0% g/mL, respectively; P<0.05 for both). Plasma sodium concentrations significantly

decreased from baseline for water and alcoholic beer (-3.9% mmol/L and -3.7% mmol/L, respectively; $P<0.01$ for both). Plasma potassium concentrations significantly increased before and after the trials in the alcoholic beer group (+8.5% mmol/L; $P<0.05$). All significant findings were compared to baseline. The difference between trial groups for urine specific gravity, plasma sodium concentrations, and plasma potassium concentrations were not significant. Plasma sodium concentrations decreased significantly with one minute remaining in the trial for the water and beer groups ($P<0.01$). Plasma potassium concentrations increased significantly in the last minute of the trial in the beer group only ($P<0.05$). Meanwhile, the non-alcoholic beer decreased plasma sodium concentrations and increased plasma potassium concentrations, but this change was not significant ($P>0.05$). Urine excretion, sweat rate, and total water evaporation loss were not significant among water, beer, or the non-alcoholic beer ($P=0.35$, $P=0.2$ or $P=0.36$, respectively) [51]. These alterations in electrolyte concentrations based on drink type identify that the sodium and potassium contents of non-alcoholic beer may be beneficial for performance. It has been well-established that alcohol decreases exercise performance [52], but non-alcoholic beer may provide increased electrolytes to the body, which may increase performance compared with water alone. These results should be interpreted with caution due to the small sample size of male soccer players.

Hydration and Aging

Although many researchers have investigated fluid consumption on exercise performance, many have conducted these studies in younger male athletes. Few have performed research in recreational athletes over a large age range.

In a cross-sectional study, Puga et al. [53] evaluated the hydration status in 96 older Spanish adults, 65 to 93 years of age (57 women and 36 men). All participants were asked to complete a food frequency questionnaire (FFQ) and Drink Questionnaire. To determine total body water, Puga et al. [53] utilized the Watson et al. [54] and Hume et al. [55] equations. Participants were assigned into three age categories: young older adults (65 to 74 years of age), old older adults (75 to 80 years of age), very old older adults (>80 years of age).

When evaluated using the Hume et al. [55] equation, total body water was lower in women among all age ranges (young older: 34.2 L, old older: 34.8 L, very old older adults: 32.2 L) compared to men (young older: 42.7 L, old older: 39.5 L, very old older: 41.7 L). Additionally, the same relationship was reported with the Watson et al. [54] equation (women: young older: 31.4 L, old older: 34.4 L, very old older: 32.3 L; men: young older: 41.2 L, old older: 38.5 L, very old older: 37.5 L). The total body water equations were only found to be significantly different from each other for male young older adults ($P<0.001$) and male old older adults ($P<0.05$). Total water intake was highest

in those who consumed primarily water instead of other drinks for all age groups and sexes (primarily water: 650 to 750 mL/day vs other drinks: 440.1 to 639.3 mL/day; $P<0.05$ for all comparisons). Based on urine analyses, all groups were moderately dehydrated. In women, body water content was correlated with drinking water ($P=0.018$), total liquid intake ($P=0.005$), total water from solid food ($P=0.013$), and total water intake ($P=0.0001$). In men, body water content was correlated with drinking water ($P=0.0001$), total water intake ($P=0.0001$), and urine color ($P=0.024$) in the young older group. Puga et al.'s [53] research supports the notion that older adults are consistently hypohydrated and do not drink enough water.

Pickering et al. [56] evaluated the relationship between endurance training on water compartments and cardiac function in 10 sedentary older adults, 62 ± 2 years of age (six women, four men), who participated in a supervised cycling intervention for three sessions a week for four months. Participant's VO_2max significantly increased after four months, compared to baseline and two months ($P<0.01$ for both comparisons). There was an increase in fractional shortening, which is the percent change on ventricular diameter when blood pumps in and out of the heart [56], from baseline to two months (35.0 ± 7.2% vs 40.8 ± 4.4%, respectively; $P<0.05$). There was also an increase in ejection fraction, which is the volume of blood the heart pumps into the body [56] from baseline to two months (72.0 ± 9.0% vs 79.0 ± 5.0%, respectively; $P<0.05$). End-systolic diameters, which is the diameter of the ventricle after contraction, decreased

significantly from baseline to four months (31.8 ± 7.5 mm vs 27.3 ± 3.4 mm; $P<0.05$). No differences in ECW, ICW, and total body water were reported at any point in the trial. However, plasma volume was found to significantly increase at two months, but not four months, compared to baseline ($P<0.05$). Based on the results, healthy sedentary participants were able to improve performance aerobically and improve their cardiac functioning while their body water compartment remained unaffected.

Watso et al. [57] evaluated water deprivation on hand grip exercise in older women after post-exercise ischemia. They included 15 young adult females (20 to 35 years of age) and 7 older adult females (55 to 75 years of age) to complete two experimental trials in a randomized, cross-over design study. The trials were either a euhydration control condition or a stepwise reduction in water intake over three days, with a 16-hour water deprivation period. During the euhydrated trial, all participants were asked to consume 23 mL of water for every kg of body weight each day. On day four, before they arrived at the laboratory, participants were asked to drink 250 mL of water. During the water deprivation trial, they were asked to drink 23 mL of water per kg of body weight on the first day; however, they were asked to decrease the amounts to 17 mL of water per kg of body weight on the second day, and to 10 mL of water per kg of body weight on the third day. Prior to day four, they abstained from water for 16 hours. Significantly higher plasma osmolarity concentrations were reported in older adults, regardless of trial type (euhydrated: 297 ± 5 mOsm/kg vs hypohydrated: 300 ± 4

mOsm/kg; P<0.05), compared to the younger group (euhydrated: 286 ± 2 mOsm/kg vs hypohydrated: 288 ± 2 mOsm kg/H2O; P<0.05). During the hand grip exercises and post-exercise ischemia, the younger participants had increased blood pressure responses with water deprivation compared to when they were euhydrated (systolic blood pressure, which is the pressure of the blood against the vessels during contraction of the heart [57]: 109 ± 8 mmHg vs 108 ± 6 mmHg (P<0.01); diastolic blood, which is the pressure of the blood against the vessels during filling of the heart [57]: 65 ± 5 mmHg vs 64 ± 4 mmHg, respectively; P=0.12). Blood pressure decreased in the older participants with water deprivation compared to those who were euhydrated (systolic blood pressure: 140 ± 19 mmHg vs 150 ± 21 mmHg; diastolic blood pressure: 76 ± 9 mmHg vs 78 ± 7 mmHg, respectively; P=0.12). Though blood pressure changes within groups was not significant, variation in blood pressure between the two age groups was significant (P<0.01). These results identify age-related variations in body water content and physiological responses with water restriction. Based on these results, recommendations for older adult athletes to consume more water for exercise is necessary.

Parodi et al. [58] assessed 132 older adults (38 women, 94 men), 67 to 77 years of age, with severe intermittent claudication to determine the benefits of hydration in peripheral artery disease or rest pain over a six-month period. Participants were asked to drink 2,500 mL of fluid daily, with 0.6 g/kg of body weight of albumin and 3.5 g of

salt. They were also asked to walk on a treadmill at 3 mph to determine the time and distance of claudication. These were recorded at baseline, six weeks, and after the six-month period. Participants increased their fluid intake from about 820 to 1,200 mL a day to about 2,000 to 3000 mL a day during the trial (P=0.0001). Of the 132 participants who completed the trials, significant progress was observed in feet temperature (ΔMedian: dorsum right foot: 0.4°C, P=0.02; ΔMedian: plantar right foot: 0.3°C, P=0.011; ΔMedian: dorsum left foot: 0.8°C, P=0.009; ΔMedian: plantar left foot: 0.8°C, P=0.03), pain levels (median of 4 out of 10 at six weeks to 3 out of 10 at six months), time/distance measures for claudication (ΔMedian: 5 minutes, P<0.0001; ΔMedian: 435 meters), and ankle-brachial pressures (ΔMedian: 0.15, P<0.0001). These results demonstrate that older adults with peripheral artery disease who do not consume adequate water will likely experience negative consequences. Proper hydration has been shown to lead to better exercise performance, and may help older adults with chronic conditions, except if water intake is contraindicated (e.g., congestive heart failure).

Summary

Water is essential for body functions, including general homeostasis, circulatory and metabolic functions. It has been well-established that proper hydration positively effects exercise performance and reduces cardiovascular and muscular strain. Additionally, the research presented identified a consistent lack of hydration among

athletes and non-athletes of all ages, indicating that there is a strong basis for promoting hydration in all athletes. However, there is a lack of evidence discussing the effects of hydration in recreational athletes over a large age range. Recreational athletes of all ages need to be evaluated to better understand how hydration can improve their performance.

Methodology

Original Study Design

The data utilized in this secondary investigation were collected at Drexel University from 2013 to 2020. This research was advertised around the Drexel University community and was open for students and local community members. Several secondary analyses have been published using data from the original study [59-61]. With permission from the principal investigator, Dr. Stella Volpe, this cross-sectional study of recreational athletes was used to determine the effects of water intake and body water content in recreational athletes. Data were collected on aerobic fitness via maximal oxygen consumption (VO_2max) using indirect calorimetry. Body water content (extracellular water [ECW], intracellular water [ICW], and total body water [TBW], also reported as total water content [TWC]) was assessed by bioelectrical impedance analysis (BIA). Participants were asked to consume plenty of water prior to their BIA appointment to avoid miscalculation. Physical activity was measured using Actical® accelerometers. Participants wore Actical® accelerometers for one week. Participants also kept an activity log of their exercise during the same week they wore the Actical® accelerometers to provide more detailed information about their exercise. Water consumption was assessed by asking participants how much water they consumed the day prior to each visit (two time points). Participants were asked

"Approximately how many cups of water did you have yesterday?" and their responses were recorded.

Dietary data were collected from the 2005 Block Food Frequency Questionnaire (FFQ) to assess dietary intake within the previous year. A guide for portion size was provided to assist participants with completing the FFQ. Participants were a part of the experimental trial for a period of one to two weeks.

Statistical Analyses

The data were isolated and performed through R studio (RStudio 2023.12.1 Build 402 "Ocean Storm" for Windows, 2024, Posit Software, PBC, Boston, MA). Prior to any analyses, body mass index (BMI) was calculated for all participants by the formula: body weight (kg) divided by height (meters squared). Secondly, ages of participants were grouped into three ranges based on physiological changes, while still ensuring a sufficient number of participants were in each group [62]. Initial analyses of the data included confirming that linear model assumptions were met, including normal distribution, using residual analyses (Figure 1). This was conducted by assessing linear models of VO_2max with water consumption, body water content (ECW, ICW, TBC), and all covariates (age, sex, body weight, height, BMI, kilocalories [kcal] vigorous activity).

After these comparisons were verified, summary data of all variables were collected. Additionally, all water variables were compared using linear regression to initially ensure variations in their findings to avoid doubling water variables with similar relationships. Once preliminary analyses were completed, age groupings were coded in R studio, using the "tidy verse" package to allow for further analyses between different age ranges.

To answer the question of which water variable was the most significant predictor of VO_2max, a linear model was fitted. The linear model assessed two-way interactions between VO_2max and all covariates (age, sex, body weight, height, kilocalories [kcals] used in vigorous activity) or water variables (water consumption at visit 1, water consumption at visit 2, and ECW, ICW, and TWC). The linear model also assessed interactions up to three-ways, meaning VO_2max was compared with the covariates and water variables combined to evaluate three variables at once. A stepwise linear regression was then used to select the best model using Bayesian information criterion (BIC) [63]. With the appropriate model selected, all variables were collectively cross examined with VO_2max, using a type three analysis of variance (ANOVA) to determine which variables were found to be significant. The type three ANOVA was used specifically because it allowed for analyses of more than just two variables at a time, thus allowing evaluation of three-way interactions more precisely. Once the ANOVA was completed, linear regression of the significant water variable was plotted

showing variations in age and sex. After the most important water variable was identified and graphed, each water variable was isolated using the same model to determine if any other water variables were significant when assessed independently. The same stepwise linear regression procedure was followed, and if the variable was found to be significant, further inference was conducted and data were plotted.

Results

Participant Data

The original study had a total of 415 participants; however, after adjusting for missing data, 141 individuals (65 females, 76 males) were included in the secondary exploratory analyses. There were 55 participants 18 and 29 years of age, 75 participants were 30 to 49 years of age, and 14 participants were 50 years of age and older. All participants exercised at least three times per week, with 107 of the 141 exercising five or more times a week. Additionally, among all participants three were on proton pump inhibitors, two were on hypertensive medication, one was on a beta blocker, and one was on a diuretic.

Maximal Oxygen Consumption

Among the participants who were included in the secondary analyses, the overall average VO_2max among ages varied quite widely (Table 1). Those within the youngest group had the highest average VO_2max and the highest minimum VO_2max, but not the highest maximum (Table 1). Those 30 to 49 years of age had the highest maximum VO_2max. Those 50 years of age and older had the lowest mean VO_2max and the lowest minimum VO_2max and lowest maximum VO_2max. When further evaluated by sex, VO_2max had a similar trend in age for males, but females did not show the same

trend (Table 2). Females had consistently lower VO_2max values across all age ranges compared to males.

Water Variables

Water variables were evaluated for mean, minimum and maximum values by age and sex (Table 3). Those 18 to 29 years of age had the highest ECW, ICW and TWC, but lower minimum values for ECW, ICW and TWC compared to the two other age groups and compared to the overall average. Those 18 to 29 years of age also had lower maximum ECW, ICW and TWC concentrations compared to those 30 to 49 years of age. Water consumption, however, varied widely between the two time points collected for each age group. With respect to water consumption, those 18 to 29 years of age had the highest mean and maximum water consumption assessed at time point 1. However, at time point 2, those 30 to 49 years of age matched the water consumption of the younger age group for time point 1. Those 50 years of age and older consistently consumed less water when assessed at both time points but had a higher minimum intake at time point 1 compared to both other age groups. Maximum oxygen consumption was found to be significantly correlated with age, height, BMI, kcals from vigorous activity (Table 4 and Figures 2 to 5). For every 0.41 cm decrease in height, VO_2max significantly increased. Body mass index had an inverse relationship with VO_2max; for every 1.62 decrease in BMI, it was estimated that VO_2max would increase significantly (Table 4). With respect

to vigorous physical activity, for every 0.67 kcals expended, VO_2max was significantly increased (Table 4). The plotted model helps to visualize these correlative relationships (Figures 2 to 5).

After initial evaluation of coefficients with VO_2max the full linear model was evaluated, and Bayesian Information Criterion was used to isolate the most important variable of the model. The initial model included all water variables and all coefficients combined. After isolation, the type three ANOVA test indicated that ECW not only had the strongest correlation with VO_2max compared to ICW, TWC and water consumption at both time points, but ECW was also the only water variable found to be significant when all water variables were assessed. Extracellular water was the only water variable found to be significant to remain in the full model ANOVA table after elimination with Bayesian Information Criterion (Table 5).

While the full model was only able to find significance in ECW compared with VO2max, further analyses of the data included all other water variables evaluated separately in individual linear models to determine if they were significant. When type three ANOVA tests were conducted for each water variable independently, significance was observed for ICW and VO_2max (Table 6). With significance found for ICW, further analyses were conducted and a relationship between ICW with VO_2max and age was observed. Intracellular water significantly affected VO_2max alone; however, when age and ICW both were evaluated with VO_2max, a strong association was observed (Table

7). Water consumption at time points 1 and 2 did not significantly correlate with VO_2max. Additionally, age, BMI, and kcals from vigorous activity were consistently found to be significant when compared with VO_2max.

When age and sex were accounted for in the equation, unique relationships were observed in ECW, ICW, and TWC when compared with VO_2max. Extracellular water had the most significant positive relationship with VO_2max for those 18 to 29 years of age and ≥50 years of age, but moderate effects on those 30 to 49 years of age (Figure 6). Alternatively, ICW had a positive relationship with VO_2max for those 18 to 29 years of age, and moderate effects in those 30 to 49 years of age. However, those ≥50 years of age had a negative association with ICW and VO_2max (Figure 7). The association of TWC and VO_2max by age and sex was nearly identical to that of ICW and VO_2max (Figure 8). With increasing ECW, there were no differences observed between women and men, 18 to 29 years of age, for VO_2max. Nevertheless, women, 30 to 49 years of age, had consistently lower VO_2max than men of the same age group with increasing ECW. Additionally, women >50 years of age had consistently higher VO_2max than men >50 years of age with increasing ECW concentrations (Figure 6). Sex-related variations were consistently different across all ages with respect to ICW and TWC (Figures 7 and 8).

Total water content also was significantly associated with VO_2max (Table 8). When evaluated separately, TWC had a similar relationship to VO_2max as ICW. As observed with ICW, VO_2max significantly increased with an increase in TWC for those

18 to 29 years of age and 30 to 49 years of age. Those >50 years of age, however, had decreases in VO_2max with increasing TWC (Figure 8). These variations by age were all found to be significant (Table 9). However, the three-way interaction for sex, age and VO2max with TWC was not significant.

Table 1. Maximal Oxygen Consumption (VO_2max) by Age

	VO_2max (mL/kg/min)		
Age Groups	**Mean ± SD**	**Minimum**	**Maximum**
18 to 29 years	47.8 ± 10.3	32.0	67.9
30 to 49 years	41.4 ± 10.9	22.8	72.2
≥ 50 years	30.99 ± 10.3	20.8	46.3
All ages combined	42.9 ± 10.9	20.8	72.2

mL: milliliters; kg; kilograms; min: minute; SD: Standard deviation
The table shows the VO_2max of all participants based on their age groups. Values include the mean, minimum and maximum VO_2max values for all age groups.
No significant differences were observed for any of the above variables.

Table 2. Maximal Oxygen Consumption (VO_2max) by Sex and Age

	VO_2max (mL/kg/min)					
	Females			**Males**		
Age groups	**Mean ± SD**	**Minimum**	**Maximum**	**Mean ± SD**	**Minimum**	**Maximum**
18 to 29 years	43.95 ± 10.3	32.00	66.50	49.61 ± 10.3	32.8	67.90
30 to 49 years	36.72 ± 10.9	22.80	52.00	47.56 ± 10.4	25.50	72.20
≥50 years	29.80 ± 10.3	20.80	35.80	32.01 ± 9.8	22.60	46.30
All ages combined	37.97 ± 10.9	20.80	66.50	47.13 ± 10.4	22.60	72.20

mL: milliliters; kg; kilograms; min: minute; SD: Standard deviation

The table shows the VO_2max of all participants based on their age and sex. Values include the mean, minimum and maximum VO_2max values for both sexes within each age group. No significant differences were observed for any of the above variables.

Table 3. Body Water Content and Water Consumption of All Participants

	Mean ± SD	Minimum	Maximum
18 to 29 years of age			
ECW (L)	36.55 ± 6.6	22.7	51.10
ICW (L)	61.63 ± 11.2	38.4	85.10
TWC (L)	98.34 ± 17.9	61.10	136.20
Water consumption 1 (mL)	528.74 ± 331.8	29.57	1,892.70
Water consumption 2 (mL)	1167.4 ± 824.6	118.29	3,785.41
30 to 49 years of age			
ECW (L)	33.95 ± 7.0	24.50	66.40
ICW (L)	57.12 ± 11.6	41.70	109.40
TWC (L)	91.18 ± 18.6	66.10	175.70
Water consumption 1 (mL)	446.50 ± 326.8	29.57	1,478.68
Water consumption 2 (mL)	1173.14 ± 812.6	118.29	3,785.41
≥50 years of age			
ECW (L)	35.18 ± 6.8	26.70	49.20
ICW (L)	57.20 ± 11.3	44.30	78.00
TWC (L)	92.39 ± 18.1	71.20	127.20
Water consumption 1 (mL)	393.34 ± 351.9	59.15	946.35
Water consumption 2 (mL)	909.60 ± 767.7	59.15	2,249.10
All Ages Combined			
ECW (L)	35.06 ± 7.0	22.70	66.40
ICW (L)	58.85 ± 11.8	38.04	109.40
TWC (L)	94.03 ± 18.8	61.10	175.70
Water consumption 1 (mL)	454.23 ± 326.4	29.57	1,892.70
Water consumption 2 (mL)	1148.92 ± 812.2	59.15	3,785.41

SD: Standard deviation; ECW: extracellular water; L: liters; ICW: intracellular water; TWC: total water content; Water consumption 1: water intake at first time point; Water consumption 2: water intake at second time point; mL: milliliters

The table shows the VO_2max of all participants based on their age, body water content (ECW, ICW, TWC) and water consumption at two different time points. Values include the mean, minimum and maximum body water content and water consumption within each age group. No significant differences were observed for any of the above variables.

Table 4. Coefficients Estimated Effects and Significances on Maximal Oxygen Consumption (VO_2max) (mL/kg/min) by Two- or Three-way Comparisons

Coefficients	Estimate	Standard Error	T-value	P-value
Age group (30 to 49 years)	37.0417	12.9598	2.858	0.004969*
Age group (≥50 years)	-21.3836	21.9756	-0.973	0.332344
Sex	-0.3027	3.9519	-0.770	0.939067
Height (cm)	-0.4175	0.1755	-2.379	0.018815*
BMI (kg/m^2)	-1.6166	0.2878	-5.617	0.0001*
Vigorous activity (kcals)	0.6679	0.2432	2.746	0.0069*
ECW (L)	1.2091	0.3403	3.553	0.000534*
Age group (30 to 49 years): Sex	-12.6126	4.7897	-2.633	0.00949*
Age group (≥50 years): Sex	5.8835	7.6361	0.770	0.4424422
Age group (30 to 49 years): ECW	-0.9804	0.3208	-3.056	0.002728*
Age group (≥50 years): ECW	0.1713	0.5463	0.314	0.754349

mL: milliliters; kg: kilograms; min: minute; T-value: ratio of the means of the variables assessed; cm: centimeters; BMI: body mass index; m^2: meters squared; kcals: kilocalories; ECW: extracellular water; L: liters

The table shows the significant findings of the coefficients (age, sex, height, BMI, kcals from vigorous activity) and all significant water variables (ECW) compared with VO_2max. Each coefficient was evaluated separately with VO_2max and up to three-ways with VO_2max to understand the complex interaction of coefficients with VO_2max.

*Indicates significant difference

Table 5. Type 3 Analysis of Variance (ANOVA) with All Water Variables Compared to Maximal Oxygen Consumption (VO_2max) (mL/kg/min)

	Degrees of Freedom	Sum of Squares	F-value	P-value
Age group (years)	2	803.9	21.2539	0.01*
Sex	1	0.3	0.0059	0.939
Height (cm)	1	337.0	5.6607	0.0001*
BMI (kg/m^2)	1	1878.5	31.5511	0.0001*
Vigorous activity (kcals)	1	448.9	7.3082	0.0078*
ECW (L)	1	751.4	12.6206	0.0005*
Age group: Sex	2	706.8	5.9356	0.0034*
Age group: ECW	2	723.7	6.0775	0.003*

mL: milliliters; kg: kilograms; min: minute; Degrees of Freedom: illustrate the variation of each group around the mean; Sum of Squares: shows the variation in the data by the square of the mean values; F-value: the ratio of the two mean squared values; cm: centimeters; BMI: body mass index; m^2: meters squared; kcals: kilocalories; ECW: extracellular water; L: liters

The table shows the significant findings of the ANOVA type three test after elimination of irrelevant data for all water variables compared with VO_2max up to three-ways.

*Indicates significant difference

Table 6. Coefficients Estimated Effects and Significances on Maximal Oxygen Consumption (VO_2max) (mL/kg/min) Specifically with Intracellular Water (ICW) by Two- or Three-way Comparisons

Coefficients	Estimate	Standard Error	T-value	P-value
Age group (30 to 49 years)	43.62747	13.81608	3.158	0.001977*
Age group (≥50 years)	-12.91243	23.81014	-0.542	0.588535
Sex	1.89353	4.10849	0.461	0.645653
BMI (kg/m²)	-1.22284	0.24192	-5.055	0.0001*
Vigorous activity (kcals)	0.56536	0.24442	2.313	0.022286*
ICW (L)	0.43431	0.16646	2.609	0.010142*
Age group (30 to 49 years): Sex	-16.23206	4.97551	-3.262	0.001411*
Age group (≥50 years): Sex	1.39834	7.92698	0.176	0.860253
Age group (30 to 49 years): ICW	-0.68326	0.20217	-3.380	0.000958*
Age group (≥50 years): ICW	-0.01487	0.36116	-0.041	0.967214

mL: milliliters; kg: kilograms; min: minute; T-value: ratio of the means of the variables assessed; BMI: body mass index; m^2: meters squared; kcals: kilocalories; ICW: intracellular water; L: liters

The table shows the significant findings of the coefficients, only ICW compared with VO_2max. Each coefficient was evaluated separately with VO_2max and up to three ways with VO_2max to understand the complex interaction of coefficients on VO_2max.

*Indicates significant difference

Table 7. Type 3 Analysis of Variance (ANOVA) Specifically with Intracellular Water (ICW) Compared to Maximal Oxygen Consumption (VO_2max) (mL/kg/min)

	Degrees of Freedom	Sum of Squares	F-value	P-value
Age group (years)	2	821.3	6.6651	0.00176*
Sex	1	13.1	0.2124	0.64565
BMI (kg/m^2)	1	1574.2	25.5500	0.0001*
Vigorous activity (kcals)	1	329.7	5.3506	0.0222858*
ICW (L)	1	419.4	6.8073	0.0101422*
Age group: Sex	2	831.6	6.7485	0.0016275*
Age group: ICW	2	799.0	6.4840	0.0020692*

mL: milliliters; kg; kilograms; min: minute; Degrees of Freedom: illustrate the variation of each group around the mean; Sum of Squares: shows the variation in the data by the square of the mean values; F-value: the ratio of the two mean squared values; BMI: body mass index; m^2: meters squared; kcals: kilocalories; ICW: intracellular water; L: liters
The table shows the significant findings of the ANOVA type 3 test after elimination of irrelevant data, and only ICW compared with VO_2max up to three ways.
*Indicates significant difference

Table 8. Coefficients Estimated Effects and Significances on Maximal Oxygen Consumption (VO_2max) (mL/kg/min) Specifically with Total Water Content (TWC) by Two- or Three-way Comparisons

Coefficients	Estimate	Standard Error	T-value	P-value
Age group: 30 to 49 (years)	38.23800	13.58354	2.815	0.005643*
Age group: ≥50 (years)	-22.01148	23.18665	-0.949	0.344235
Sex	0.35409	4.04706	0.087	0.930427
Height (cm)	-0.38173	0.17383	-2.196	0.0229880*
BMI (kg/m^2)	-1.60417	0.29557	-5.427	0.0001*
Vigorous activity (kcals)	0.65481	0.24359	2.688	0.008133*
TWC (L)	0.44374	0.12886	3.444	0.000775*
Age group (30 to 49): Sex	-13.21245	5.01329	-2.635	0.009432*
Age group (≥50): Sex	5.63468	7.90602	0.713	0.477314
Age group (30 to 49): TWC	-0.37525	0.12494	-3.004	0.003206*
Age group (≥50): TWC	0.08301	0.21906	0.379	0.705355

mL: milliliters; kg; kilograms; min: minute; T-value: ratio of the means of the variables assessed; cm: centimeters; BMI: body mass index; m^2: meters squared; kcals: kilocalories; TWC: total water content; L: liters

The table shows the significant findings of the coefficients; only TWC was associated with VO_2max. Each coefficient was evaluated separately with VO_2max and up to three-ways with VO_2max to understand the complex interaction of coefficients on VO_2max.

*Indicates significant difference

Table 9. Type 3 Analysis of Variance (ANOVA) Specifically with Total Water Content (TWC) Compared to Maximal Oxygen Consumption (VO_2max) (mL/kg/min)

	Degree of Freedom	Sum of Squares	F-value	P-value
Age group (years)	2	1265.44	21.18	0.0001*
Sex	1	1582.12	26.48	0.0001*
Height (cm)	1	1342.6	22.47	0.0001*
BMI (kg/m^2)	1	1805.5	30.22	0.0001*
Vigorous activity (kcals)	1	435.13	7.28	0.0079*
TWC (L)	1	357.04	5.98	0.0158*
Age group: Sex	2	59.86	1.00	0.3700
Age group: TWC	2	352.83	5.91	0.0035*

mL: milliliters; kg; kilograms; min: minute; Degrees of Freedom: illustrate the variation of each group around the mean; Sum of Squares: shows the variation in the data by the square of the mean values; F-value: the ratio of the two mean squared values; cm: centimeters; BMI: body mass index; m^2: meters squared; kcals: kilocalories; TWC: total water content; L: liters

The table shows the significant findings of the ANOVA type three test after elimination of irrelevant data for TWC compared with VO_2max up to three-ways.

*Indicates significant difference

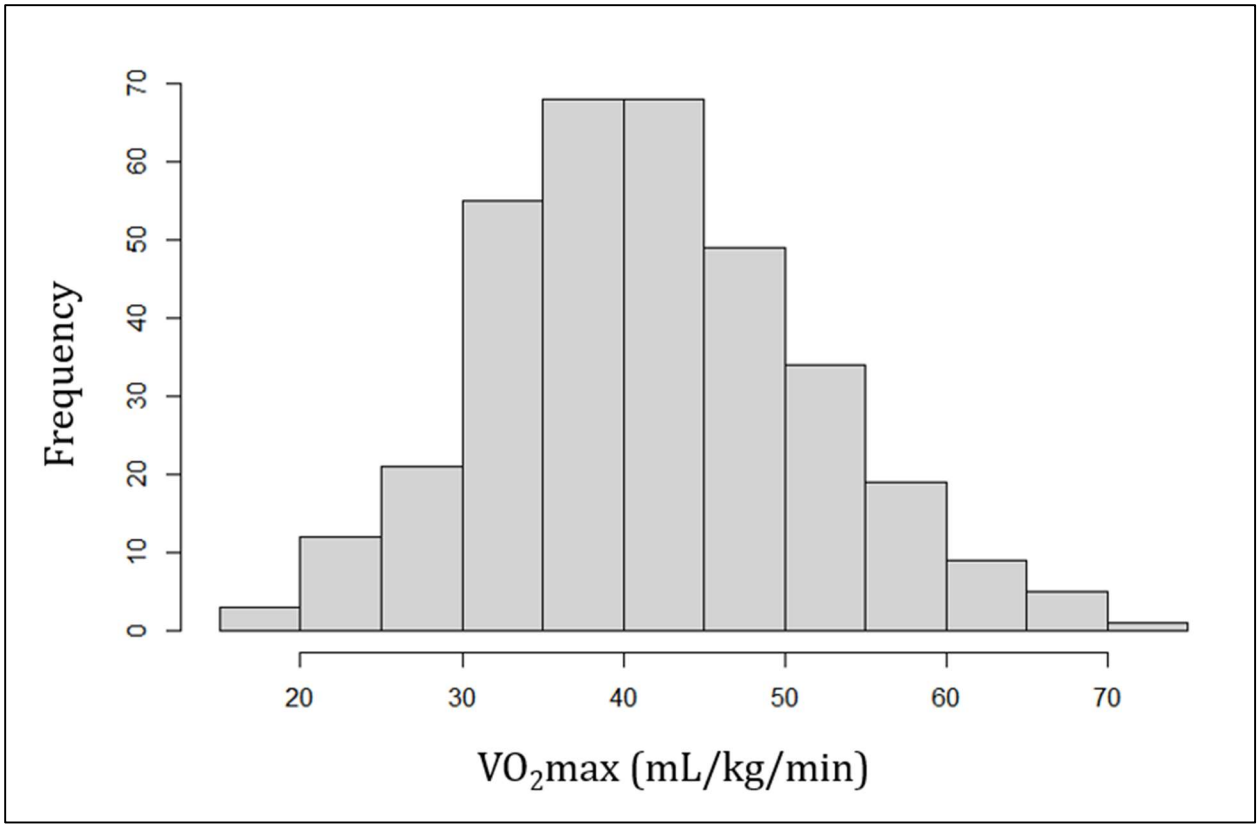

Figure 1. Histogram of maximal oxygen consumption (VO_2max).
The figure depicts the distribution of VO_2max among all participants to ensure normal distribution was met prior to statistical analyses. VO_2max values were normally distributed ($P>0.05$).

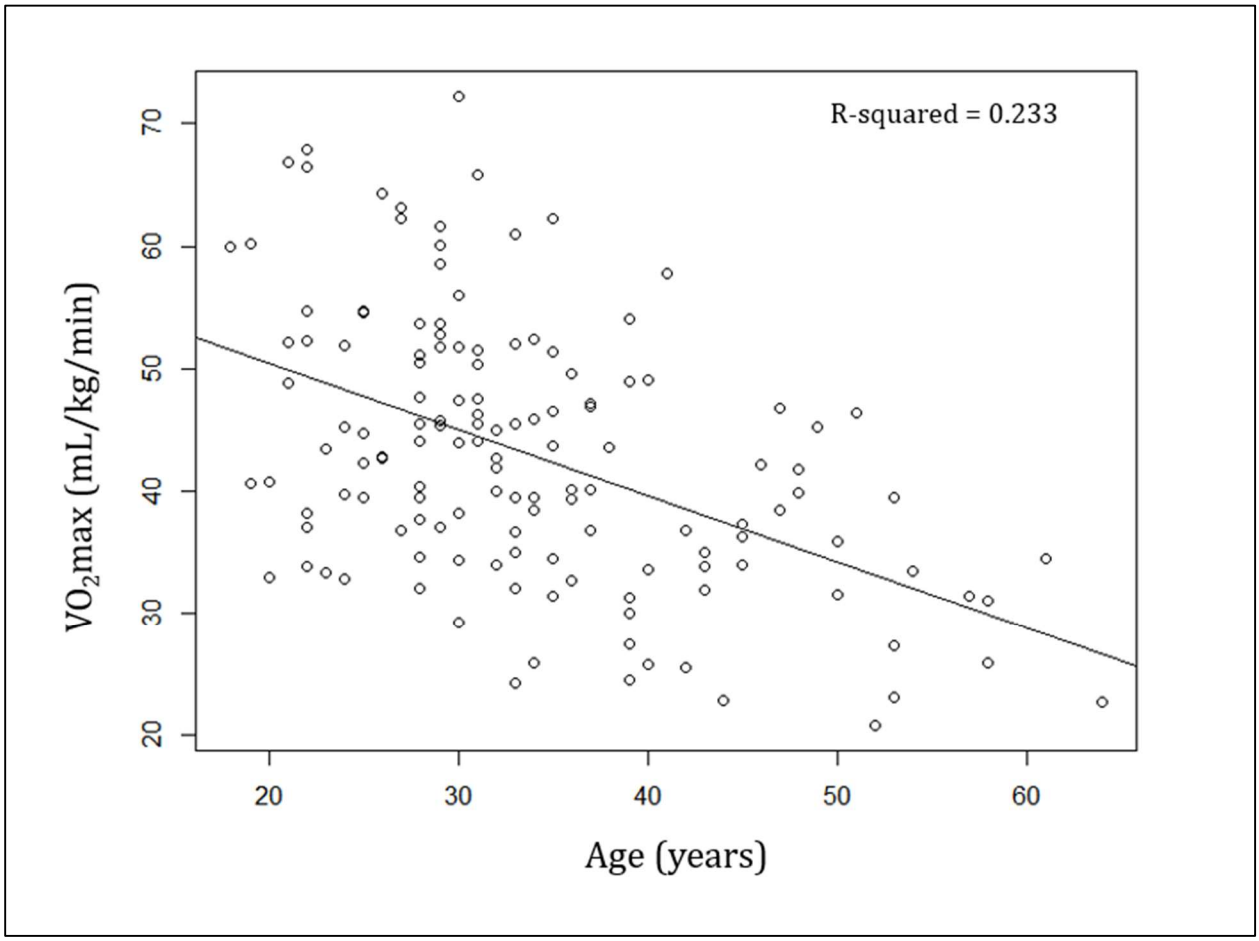

Figure 2. Age compared to maximal oxygen consumption (VO_2max) scatter plot. Plotted participant data for age and VO_2max to visualize the trended relationship. mL: milliliters; kg: kilograms; min: minute
R^2=0.233 (identifying the model's ability to predict the outcomes) and 139 degrees of freedom (evaluation of independent variable quantities) (P=0.0001)

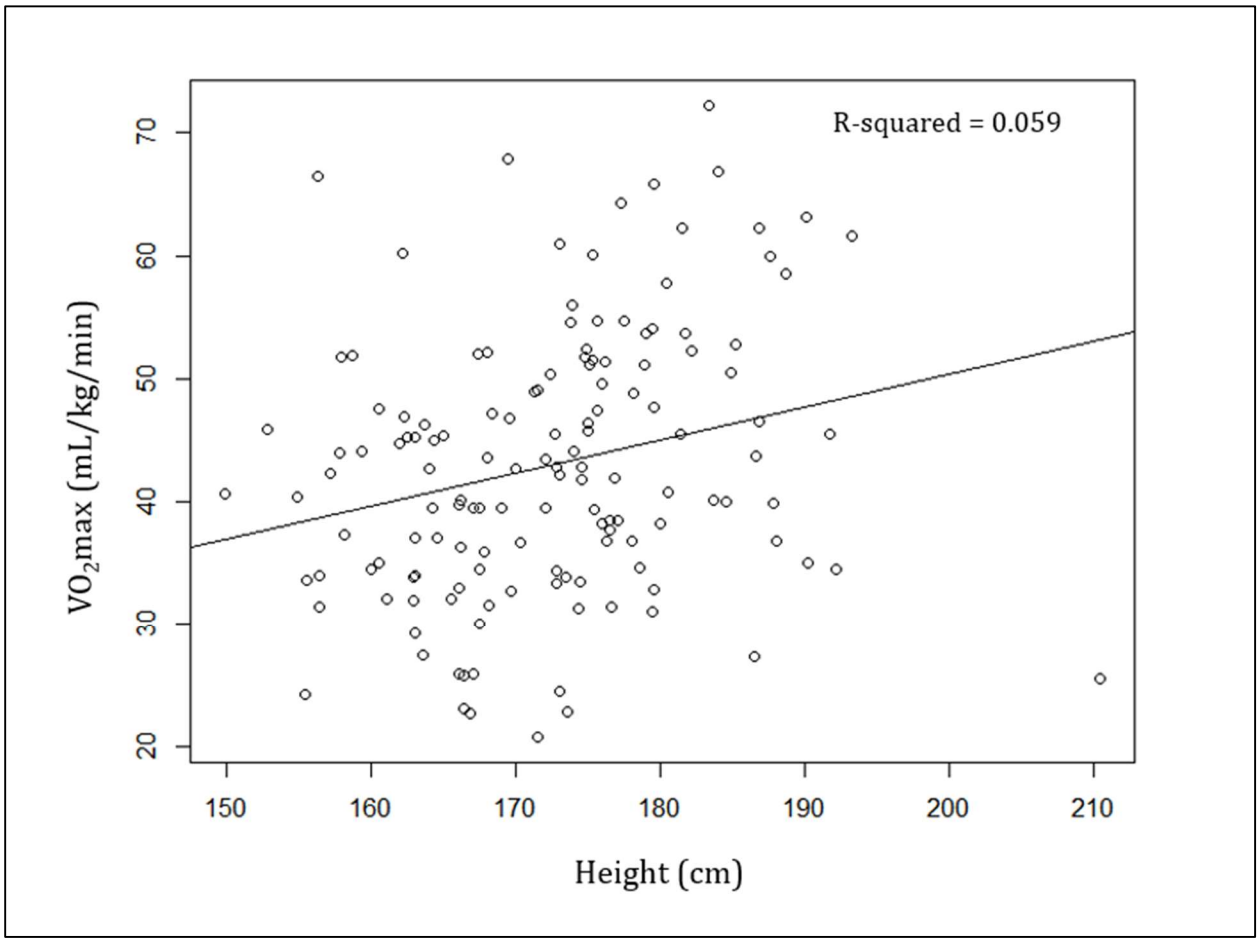

Figure 3. Height compared to maximal oxygen consumption (VO_2max) scatter plot. Plotted participant data for height and VO_2max to visualize the trended relationship. mL: milliliters; kg; kilograms; min: minute; cm: centimeters
R^2=0.059 (identifying the model's ability to predict the outcomes) and 139 degrees of freedom (evaluation of independent variable quantities) (P=0.01)

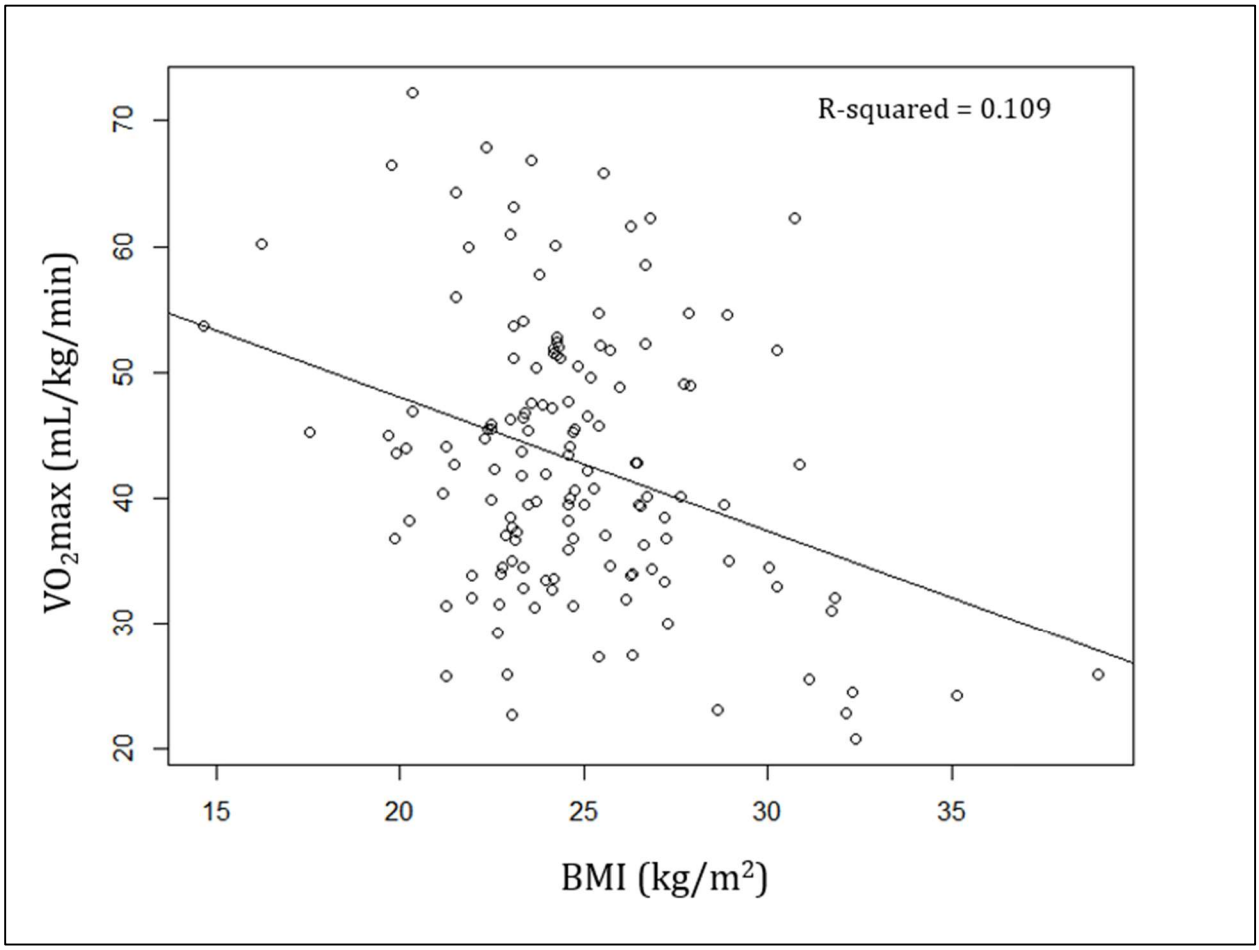

Figure 4. Body mass index (BMI) compared to maximal oxygen consumption (VO_2max) scatter plot.

Plotted participant data for BMI and VO_2max to visualize the trended relationship.

mL: milliliters; kg; kilograms; min: minute; m^2: meters squared.

R^2=0.109 (identifying the model's ability to predict the outcomes) and 139 degrees of freedom (evaluation of independent variable quantities) (P=0.0001)

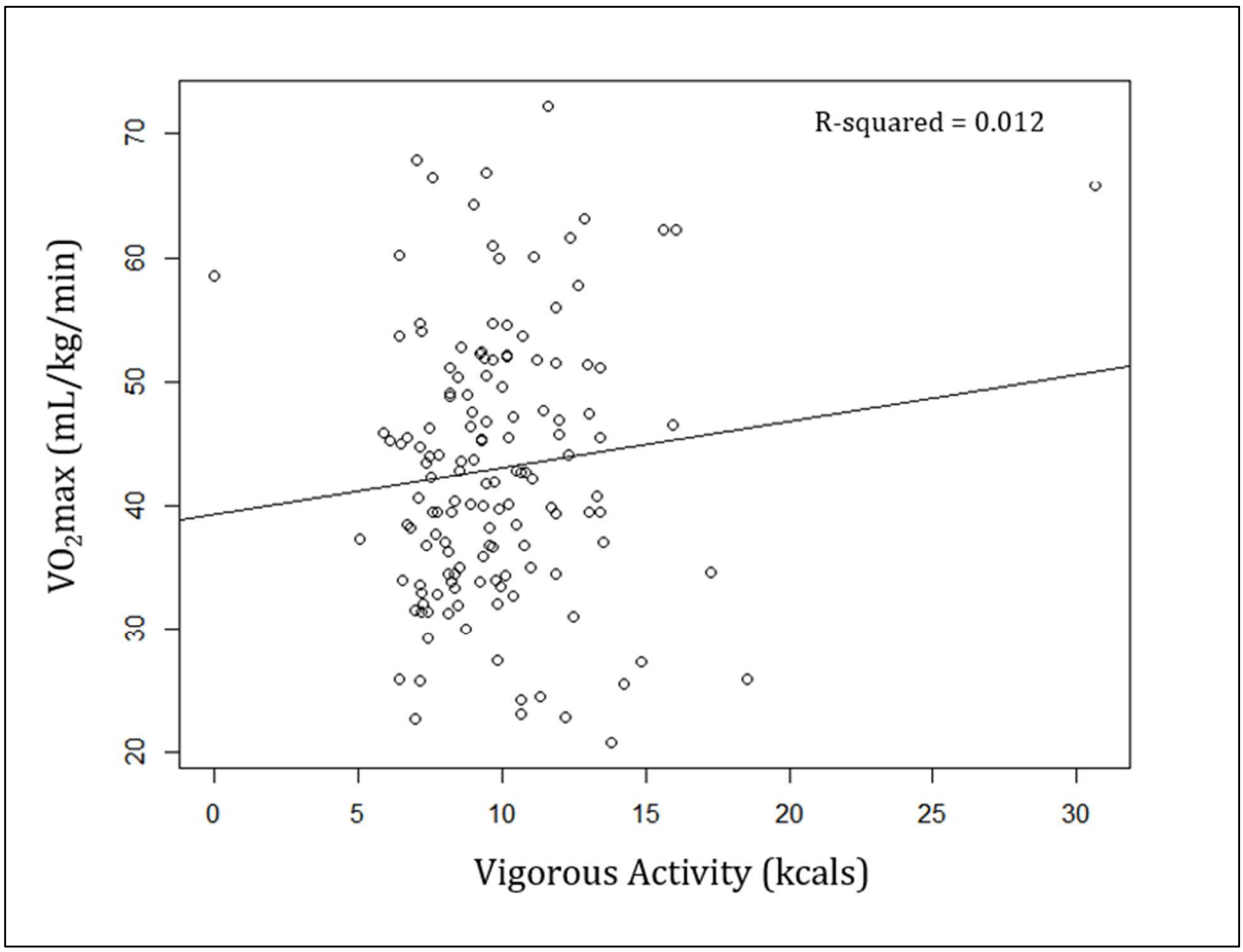

Figure 5. Vigorous activity in kilocalories (kcals) compared to maximal oxygen consumption (VO_2max) scatter plot.
Plotted participant data for vigorous activity in kcal and VO_2max to visualize the trended relationship.
mL: milliliters; kg; kilograms; min: minute; kcals: kilocalories
R^2=0.012 (identifying the model's ability to predict the outcomes) and 139 degrees of freedom (evaluation of independent variable quantities) (P=0.01)

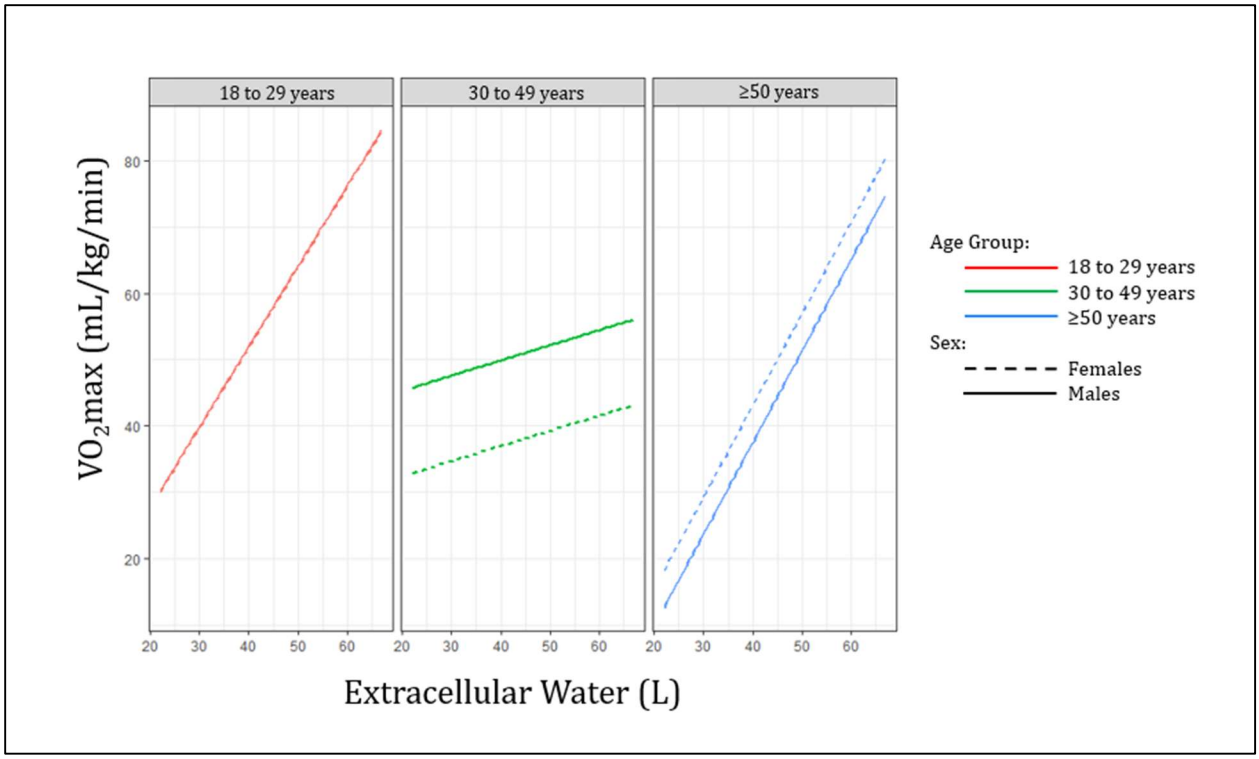

Figure 6. Linear Model of extracellular water (ECW) compared to maximal oxygen consumption (VO_2max) by age and sex.

The model predicted marginal effect of ECW on VO_2max by age and sex. Mean covariates were used to better illustrate the raw data relationships of VO_2max with ECW by age and sex.

mL: milliliters; kg; kilograms; min: minute; L: liters

The three-way interaction among ECW, age and VO_2max was significant (P=0.003)

The three-way interaction among sex, age and VO_2max was significant (P=0.0034)

Note: the female and male lines for those in the 18 to 39 years of age group overlap, which is why it may look like a single line.

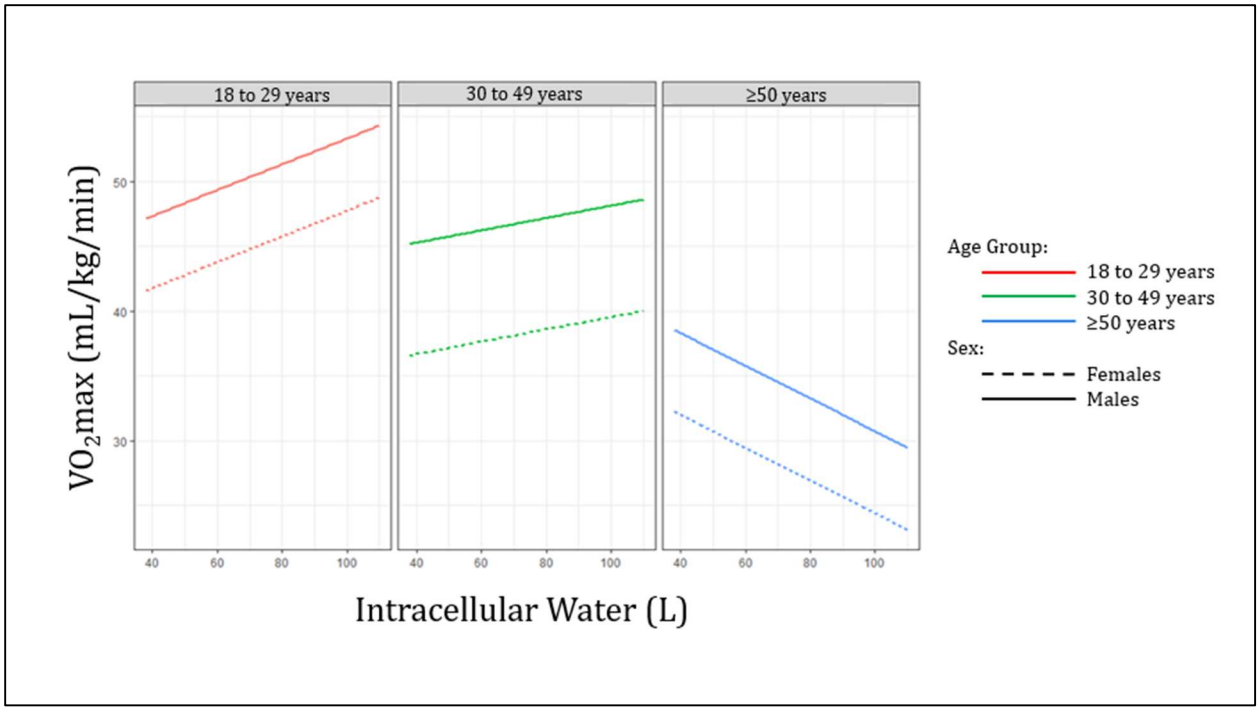

Figure 7. Linear model of intracellular water (ICW) compared to maximal oxygen consumption (VO_2max) by age and sex.

The model predicted marginal effect of ICW on VO_2max by age and sex. Mean covariates were used to better illustrate the raw data relationships of VO_2max with ICW by age and sex.

mL: milliliters; kg; kilograms; min: minute; L: liters

The three-way interaction among ICW, age and VO_2max was significant (P=0.0021)

The three-way interaction among sex, age and VO_2max was significant (P=0.0016)

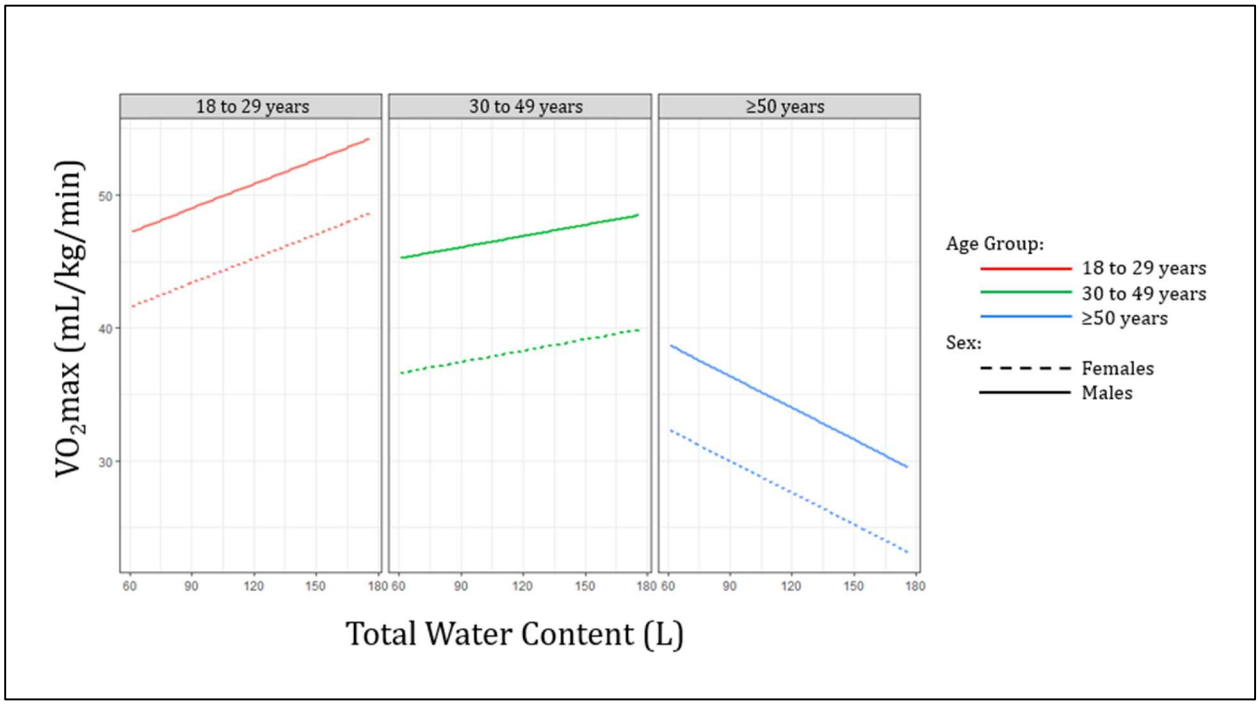

Figure 8. Linear model of total water content (TWC) compared to maximal oxygen consumption (VO_2max) by age and sex.
The model predicted marginal effect of TWC on VO_2max by age and sex. Mean covariates were used to better illustrate the raw data relationships of VO_2max with TWC by age and sex.
mL: milliliters; kg; kilograms; min: minute; L: liters
The three-way interaction among TWC, age and VO_2max was significant (P=0.0035)
The three-way interaction among sex, age and VO_2max with TWC was not significant (P=0.37)

Discussion

Body Water Content and Water Consumption

The most prominent finding from this study was the unique relationship between extracellular water (ECW) and maximal oxygen consumption (VO_2max). The results identified that VO_2max was positively associated with increases in ECW. This relationship suggests that ECW could affect athletic performance. The body has many regulatory pathways to maintain normal body water concentrations. For example, Zhang et al. [33] reported that water restrictions increased intracellular water (ICW) but decreased ECW. This response helps to illustrate the unique roles of both ICW and ECW and their importance in the body. The present evidence indicates that, when body water content decreases, it is preserved within the intracellular compartments for cellular functioning. However, because ECW is primarily comprised of sodium, sweat loss and other forms of water loss decrease the ECW concentration more rapidly. Additionally, extracellular fluid is comprised of interstitial and plasma fluid (blood volume), thus, decreases in ECW would result in decreased plasma volume [12,13]. With lower blood volumes, oxygen is transported less readily and affects the capacity for energy production [12]. Though participants among this study were recreationally active, some were more active than others; of those in the 30 to 49 years of age group, 68% exercised five or more times a week.

Additional significant findings included the relationships of ICW and total water content (TWC) with VO_2max. Like ECW, VO_2max increased with increased ICW and TWC for those 18 to 29 years of age and 30 to 49 years of age. These findings further promote the effects of body water content on markers for performance. However, few researchers have discussed body water concentration and performance specifically. Southard and Pugh [35] reported similar results when they observed that VO_2max was decreased with dehydration. While, Wang et al. [40] reported that increased energy expenditure and performance with increased hydration. Intracellular water and TWC have crucial roles in cellular metabolism and oxygen utilization. Increased water overall, and intracellularly, can positively affect the cells' capacity for oxygen diffusion and energy production. [13]

One less expected finding was that water consumption was not significantly associated with VO_2max. It was theorized that water consumption would show a positive association with VO_2max. Juett et al. [41] reported that decreased water consumption had clear effects on heart functioning. Adams et al. [43] determined that increased hydration improved power. The lack of association with water intake and VO_2max could be related to the data collection process for water consumption. Participants were simply asked to self-quantify their water intake the day prior to each of their two visits to the laboratory. The data would be more reliable if more well-established water consumption methods were used [64].

Age

Age had a significant relationship with VO_2max in this study. An increase in age was associated with a decreased VO_2max. The results showed that increased ICW and TWC were associated with a decreased VO_2max in those >50 years of age. Although there is a paucity of research in older adults who exercise, none appear to target the effects of body water content on athletic performance, and thus, it is difficult to evaluate these findings. However, Lorenzo et al. [13] reported that the aging process decreases muscle mass, and therefore, decreases intracellular water capacity.

In addition to body water content, water intake was evaluated in this study. The present study provides evidence to suggest that, with increasing age, water intake decreases. Those ≥50 years of age consumed 13% to 21% less water than the overall average. Puga et al. [53] reported that older adults consume far less fluid than their younger counterparts. Additionally, the body responses to lower water intake are affected with age, like the thirst response, and therefore, older adults are more likely to become dehydrated [1,2,6]. These research findings could help to explain the age-related differences seen in this study and may indicate a gap in the literature.

Sex

The final significant finding was the sex-related differences in VO_2max. Overall, women had lower VO_2max values than men, which for the most part, remained the same when sex, body water content and VO_2max were evaluated. This is consistent with past research on sex differences by Xiang et al. [17] and others [65, 66], who also reported a lower VO_2max in women compared to men. The only exceptions to these findings were in those 18 to 29 years of age; women and men had nearly identical increases in VO_2max with increasing ECW. However, women >50 years of age had higher a VO_2max with increasing ECW compared to men.

Water intake among participants by sex was evaluated. The results of this study indicate that women, regardless of age, consumed less water than men. With respect to water consumption, Volpe et al. [23] and Ramos-Jiménez et al. [45] reported that women consumed more water than men. Perhaps women, 18 to 29 years of age and >50 years of age who had higher body water content consumed more water.

Strengths

There are several strengths of this study. This study had a large sample size, even though it could not include all the participants from the original study. This study evaluated a wide range of ages, including older active adults, who are not researched as

often as younger athletes. Additionally, the evaluator of this study had no association with the original study design, and therefore, avoided any possible biases involving data collection.

Limitations

Although useful and valuable information can be obtained from this study, there were several limitations. First, this was a cross-sectional study, and therefore, no cause and effect can be determined. In addition, there was not an even distribution of participants within each age group. The participants also participated in a wide range of sports and activities. An additional limitation of the study design was that participants were advised to drink plenty of water before they were evaluated by bioelectrical impedance analysis (BIA). This recommendation could have affected the BIA values, and their reported water consumption could have been skewed from their typical intake. Though the data collected were well recorded and valuable, the primary aim of the original study was not designed to assess body water content or water consumption. Because water consumption was not a primary outcome, more rigorous forms of data collection for water were not utilized. Finally, participants were asked to recall and report their water consumption, and thus, some recall bias could have been present and affected the data outcomes.

Conclusion

This study design aimed to evaluate if differences in body water content and water consumption of recreational athletes among a wide age range and of both sexes would be associated with VO_2max. Although no relationship was found between water consumption and VO_2max, there was some significant correlations with body water content and VO_2max. The results isolated the positive relationship between ECW, ICW, and TWC on VO_2max with clear variations by age and sex. Thus, this research suggests that a person's age, sex, and body water concentration is related with VO_2max.

Few researchers have evaluated body water content or water consumption on VO_2max in athletes among a varying age group. Future research of athletes among a wide range of ages is recommended. Prospective studies on body water content and water consumption are needed.

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