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REVIEW

Reference Values for Hydration Biomarkers: Optimizing Athletic Performance and Recovery

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Abstract: The negative effects of dehydration or overhydration on exercise performance and health are widely recognized. However, the interindividual variability of fluid imbalances among athletes and across various sports is large, due to the complex interactions of physiological, environmental, and sport-specific factors. Such complexity not only makes it difficult to predict fluid needs prior to competition or training sessions, but also supports the creation of an individualized hydration plan (IHP) for each athlete. Measurements of valid, field-expedient biomarkers such as body mass change, urine concentration, and thirst enable ongoing monitoring of an athlete's hydration state and are integral components of an IHP. Unfortunately, no extensive repository of sport-relevant hydration biomarker data exists. Therefore, this narrative review presents a novel inventory of pre- and post-exercise reference values for body mass change, urine specific gravity, and subjective rating of thirst. These reference values were identified via electronic database searches that discovered field studies of competitive events, weight category sports, training sessions, and routine daily activities. We propose that comparing an athlete's real-time body mass change, urine specific gravity, and thirst rating to previously published reference values will clarify the extent of dehydration or overhydration, guide rehydration efforts, and optimize subsequent exercise performance, recovery, and health.

Keywords: urine specific gravity, thirst, runner, cyclist, swimmer, triathlete

Introduction

Deficits of total body water are relevant to all athletes because substantial fluid losses degrade competitive sport performance[1–4] and increase the risk of exertional heat illnesses, especially heat exhaustion.[5–9] Dehydration potentiates hyperthermia, increases cardiovascular strain, and elevates perceived exertion. Specifically, a body mass loss of 3–4% induced by dehydration may decrease muscular strength by 2%, muscular power by 3%, and high-intensity endurance exercise by 10%.[1,10] As the body water deficit increases (ie, due to unreplaced fluid losses during outdoor competition, training sessions, "making weight" in combat sports, or routine daily activities), both detrimental physiological effects (ie, which often influence exercise) and clinical signs and symptoms proliferate.[11–13]

The following documented scenarios illustrate the wide range of fluid deficits that are experienced by athletes in various team and individual sports. During hot summer months, collegiate American football linemen can lose 4–6 kg of body water during a single summer practice session,[5] and the sweat rates of tennis players and marathon runners during competition reach extremes of 3.4 and 3.7 L/h, respectively.[14,15] In moderate or cool environments, ultraendurance athletes can experience extreme body water losses (7.8–8.5 kg, 11–12% of body mass) when competing in a 12.3 h Ironman triathlon event.[16] During 1.5–2.5 h training sessions across a variety of sports (eg, European soccer, American football, tennis, cross country), body mass deficits typically range from 0.5–3.2% when fluids are readily available.[17–20] Other athletes purposefully dehydrate to qualify for lower weight classes (eg, wrestling, martial arts); this regimen can result in body water losses of 3–5%.[21,22] Even on days that are void of training or competition, it is possible for healthy young adults to incur a 2.1% body mass loss during a single day of routine activities if no fluid is consumed.[23]

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At the opposite end of the hydration continuum, some endurance athletes consume a large volume of fluid that greatly exceeds the volume of fluid which he/she lost as sweat. Because sodium is lost in sweat, the outcomes are dilution of body fluids and reduced blood concentration of sodium.[24] This phenomenon is appropriately named exertional hyponatremia or water intoxication. Not only does exertional hyponatremia degrade exercise performance (eg, due to undue fatigue), but severe cases may result in coma, pulmonary edema, cerebral edema, or death.[4] The prominent signs and symptoms include dilute urine, swollen hands, disorientation, nausea, vomiting, skeletal muscle twitching, and grand mal seizure.[25] Documented cases of symptomatic exertional hyponatremia[26,27] have shown that fluid volumes of 10.3–14.7 L were consumed during exercise lasting 4–10 h. However, exertional hyponatremia has also been verified among non-endurance athletes,[4,24] soldiers,[28] and individuals who erroneously believed that excessive water intake was beneficial to performance or health.[26] To reduce the risk of exertional hyponatremia, athletes are advised to gain no weight during exercise (ie, signifying fluid retention), and use a digital floor scale before and after exercise to confirm body weight change.[3]

The aforementioned large range of body water changes, coupled with the dynamic/complex physiological effector responses that occur when the brain senses altered body water volume or concentration,[29–33] represents great complexity that makes it difficult (ie, for clinicians, physiologists, athletes, or coaches) to accurately predict in advance the fluid deficit or excess which any athlete might experience during training or competition. This complexity explains, in part, why no single hydration biomarker allows a conclusive clinical diagnosis of dehydration for all athletes in all sport scenarios.[34–39] Thus, we recommend creating an individualized hydration plan (IHP) for each athlete which incorporates multiple biomarkers, in agreement with numerous investigators and professional organizations.[3,4,27,40–43] Specifically, we recommend three hydration indices which are inexpensive, valid, and require minimal technical expertise: body mass change, urine specific gravity, and rating of thirst. This approach provides athletes with data that is unique in the existing literature because most publications[4,44–50] provide only a single hydration biomarker measurement (eg, urine specific gravity of 1.020) or a narrow range of values (eg, body mass loss of 3–4%) for all athletes, to indicate the threshold of dehydration's detrimental effects. Using only one biomarker to assess hydration state is inferior, however, because (a) interindividual variability of fluid–electrolyte imbalances is large and is influenced by many factors;[31,51–54] and (b) research studies[31,55] have determined that combining two or three hydration indices (ie, body mass change, urine concentration, and thirst rating) improves the likelihood of distinguishing hypohydration from euhydration (ie, an optimal body water balance without underhydration or overhydration). In addition, our three criterion biomarker approach contributes importantly to the literature because no inventory of hydration biomarker data exists to guide interpretation of the unique body water changes (ie, deficits or excesses) which athletes experience in various sports.

Therefore, the purpose of this review is to provide reference values for three field expedient biomarkers: body mass change, urine specific gravity, and rating of thirst. We have assembled a novel inventory of reference values for these three hydration biomarkers from field studies that involved outdoor competitions, training sessions, "making weight" in combat sports, and performing routine daily activities with no exercise. This collection of reference values is intended for use by clinicians, athletes, coaches, and physiologists, (a) as one of multiple resources that can be utilized to create and evaluate IHP for athletes and (b) to interpret hydration status before physical training or competition, post-exercise dehydration or excess fluid intake/retention, rehydration that optimizes recovery and health, and hydration status during routine daily activities.

Search Methods

Manual searches for relevant articles were performed using advanced search operators (eg, "and", "or", "not"). These searches focused on field studies that incorporated measurements of three human hydration biomarkers: body mass, urine specific gravity, and subjective ratings of thirst. Search inclusion criteria included English language, full-text, peer-reviewed articles with adult test participants, and availability through May 1, 2024. These searches were performed in the PubMed and Google Scholar databases; they employed numerous combinations of the following keywords, during separate explorations of the title/abstract and all text fields: "athlete", "athletic", "sports", "hydration", "hydrate", "hydrated", "hydrates", "hydrating", "biomarker", "biomarkers", "index", "indexes", "indices", "indicators", "urine specific gravity", "thirst", "body mass", and "body weight". These online searches acknowledged that the authors of hydration-relevant articles rarely distinguish the term "body mass" from "body weight".

Using these search terms within PubMed and Google Scholar databases, initially 3,224 articles were identified as potentially relevant (Figure 1). After duplicate records were removed, we reviewed titles and abstracts (ie, seeking studies that reported body mass change, urine specific gravity, and a subjective thirst rating as hydration indices) to identify potentially appropriate full-length articles which should be assessed further. Also, we performed manual searches of the reference lists in these relevant articles, as well as the bibliographies found in germane systematic reviews and meta-analyses. Finally, we investigated full text (.pdf) versions of 385 articles to ascertain if they met our inclusion criteria. Figure 1 illustrates the steps in this selection process.

Results

Using the keywords, inclusion criteria, and methods described above, we accepted 16 articles for analysis within the present review. All of these 16 articles measured body mass with a floor scale and urine specific gravity with a handheld refractometer; subjective ratings of thirst were measured using one of the two methods (eg, category scale or visual analog scale) described in footnotes b and e of Table 1. Thus, the following tables present measurements of only body weight change, urine specific gravity, and subjective rating of thirst during a variety of athletic and routine daily activities. For example, Table 1 presents reference values which can be utilized by clinicians, coaches, physiologists, and athletes to develop an IHP for use during outdoor athletic competitions and training sessions.

Table 2 focuses on combat sport (ie, wrestling, boxing, judo) athletes who attempt rapid body mass loss to qualify for a weight class. Although our extensive literature search identified only a few studies of this type, values are provided for both pre- and post-weigh-in. Table 3 describes the changes of body mass, urine specific gravity, and subjective thirst ratings of two men who developed exertional hyponatremia during a 164-km summer ultraendurance cycling event.[27] In column 4, mean (± SD) values are presented for a comparison group of 31 normonatremic cyclists who participated in the same event.

In Table 1 and 2, the relationship between average body mass change and urine specific gravity ($r = 0.50$, $p = 0.013$), as well as the relationship between average body mass change and rating of thirst ($r = 0.68$, $p = 0.001$), were significantly correlated.

Table 4 and 5 describe our three criterion hydration biomarkers, as they were measured during the routine daily activities of representative, healthy young adults. The test participants in these field studies[23,68–70] were nonathletes who either performed recreational exercise (Table 4) or refrained from exercise (Table 5). The experimental design of the former study[69,70] allowed a comparison of the average differences between morning and afternoon measurements. The latter field study (Table 5) illustrates hydration biomarker perturbations that resulted from a 24-h period of water

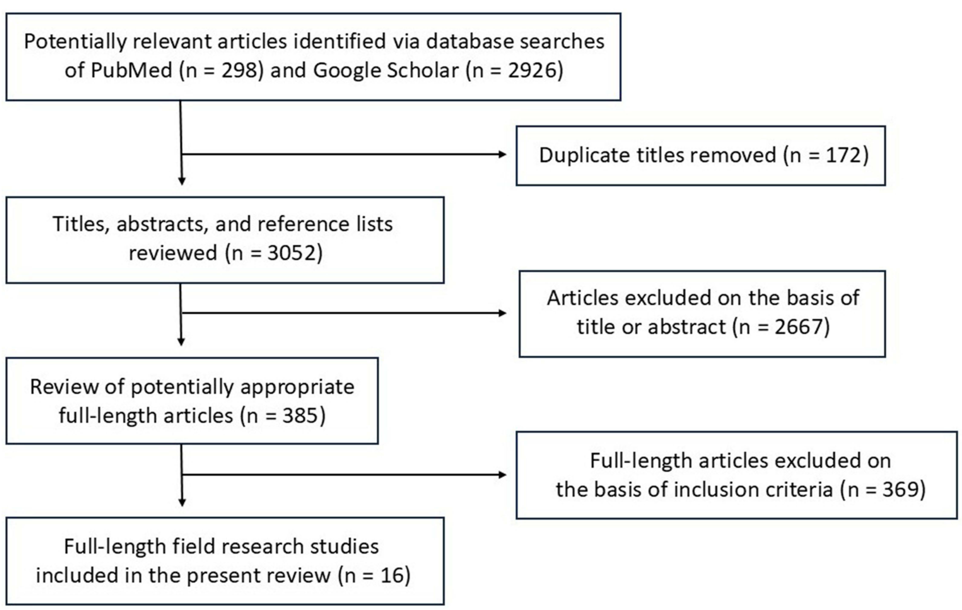

Figure 1 Selection process for the 16 field research studies which appear in the present review.

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Table 1 Hydration Biomarker Values Associated with Outdoor Athletic Competitions and Training Sessions

Sport/event, Participants (number)	Exercise Duration & Environmental Conditions		Hydration-relevant Variables	PRE [a]	POST [a]	Average Change During the Event	References
Collegiate American football players, summer training session (n = 11♂)	2.5 h; 22–32°C, 58–92%rh		Body mass (kg)	115.4 ± 18.9	114.0	−1.4 kg (−1.2%)	[20]
			Urine specific gravity	1.020	1.024	+0.004	
			Rating of Thirst [b]	4	6	+2	
Well-trained, competitive runners; 12-km summer trail race – monetary incentives (n = 8♀, 9♂)	Started the trail race normally hydrated [c]	53.2 min run time; WBGT, 27.1°C; DB, 26.3°C	Body mass (kg)	63.66	62.29	−1.37 kg (−2.2%)	[56]
			Urine specific gravity	1.009 ± 0.006	1.012 ± 0.006	+0.003	
			Rating of Thirst [b]	2 ± 1	3 ± 2	+1	
Well-trained, experienced runners; 12-km controlled pace summer trail run (n = 7♀, 7♂)	Started paced running normally hydrated [c]	1.06 h run time; WBGT, 27.8°C	Body mass (kg)	66.7	65.8	−0.9 kg (−1.3%)	[57]
			Urine specific gravity	1.013 ± 0.010	1.015 ± 0.007	+0.002	
			Rating of Thirst [b]	2 ± 1	4 ± 1	+2	
Recreational boxing, tennis, and cross-country training at sports clubs (n = 29♀, 28♂)	35–120 min [d]		Body mass (kg)	72.87 ± 14.54	72.07 ± 14.35	−0.80 kg (−1.1%)	[17]
			Urine specific gravity	1.014 ± 0.008	1.018 ± 0.007	+0.004	
			Rating of Thirst [e]	21 (0–69) [f]	60 (22–86) [f]	+39	
160-km summer road event, recreational endurance cyclists (n = 6♀)	9.0 h ride time; DB, 24.4–39.5°C; 40–83%rh		Body mass (kg)	67.32 ± 7.21	67.25 ± 7.48	−0.07 kg (−0.1%)	[58]
			Urine specific gravity	1.018 ± 0.001	1.023 ± 0.004	+0.005	
			Rating of Thirst [b]	4 ± 1	6 ± 2	+2	
160-km summer endurance road event, experienced cyclists (n = 3♀, 9♂)	6.7 h ride time; DB, 26–42°C, 17–58%rh		Body mass (kg)	87.5 ± 16.8	85.4 ± 16.8	−2.1 kg (−2.4%)	[59]
			Urine specific gravity	1.022 ± 0.008	1.026 ± 0.009	+0.004	
			Rating of Thirst [b]	2 ± 1	6 ± 1	+4	
160-km summer endurance road event, experienced cyclists (n = 26♂)	7.0 h ride time; DB, 35.5°C; 29%rh		Body mass (kg)	81.85	79.65	−2.2 kg (−2.7%)	[60]
			Urine specific gravity	1.019 ± 0.007	1.022 ± 0.008	+0.003	
			Rating of Thirst [b]	2 ± 1	6 ± 2	+4	
160-km summer endurance road event, experienced cyclists (n = 15♀)	7.7 h ride time; DB, 35°C; 32–49%rh		Body mass (kg)	64.6	63.9	−0.7 kg (−1.1%)	[61]
			Urine specific gravity	1.014 ± 0.006	1.021 ± 0.006	+0.007	
			Rating of Thirst [b]	3 ± 1	5 ± 2	+2	
160-km summer endurance road event; highly trained cyclists plus recreational enthusiasts (n = 31♂)	9.0 h ride time; 24–40°C, 40–83%rh		Body mass (kg)	85.4 ± 13.1	84.2 ± 12.7	−1.2 kg (−1.3%)	[27]
			Urine specific gravity	1.019 ± 0.007	1.023 ± 0.007	+0.004	
			Rating of Thirst [b]	2 ± 1	5 ± 1	+3	
Professional soccer players (n = 42♂)	90 min soccer match plus on-field measurements; DB, 31°C, 82%rh		Body mass (kg)	71.40 ± 7.79	70.29 ± 7.41	−1.15 kg (−1.6%)	[62]
			Urine specific gravity	1.015 ± 0.001	1.021 ± 0.001	+0.006	
			Rating of Thirst [b]	3.8 ± 1.4	4.4 ± 1.6	+0.6	

Notes: [a] Standard deviations were not reported in five of these studies; [b] This 9-point thirst intensity scale[63] presented the following options: 1, not thirsty at all; 3, a little thirsty; 5, moderately thirsty; 7, very thirsty; and 9, very very thirsty; [c] Runners began the 12-km course euhydrated and consumed 400 mL of water at 4-km and 8-km marks; [d] Ambient conditions were not reported; [e] Participants marked an "X" on a visual analog scale (VAS; 100 mm straight line flanked by "none" on the left side and "worst possible" on the right) to rate thirst intensity; [f] Data were presented as median (range).

Abbreviations: DB, dry bulb temperature; %rh, % relative humidity; WBGT, wet bulb globe temperature.

Table 2 Hydration Biomarker Values Associated with Rapid Body Mass Loss to "Make Weight" in Combat Sports[a]

Sports & Athletes (number)	Time Elapsed Between Pre & Post Observations	Hydration-relevant Variables	Pre Measurements	Post Measurements at the Weigh-in	Group Average Change [b]	References
NCAA Division I wrestlers (n = 56♂)	2 h (training session with rapid body mass loss of 3%)	Body mass (kg)	78.1 ± 1.8	75.8 ± 1.8	−2.3 kg (−2.9%)	[22]
		Urine specific gravity	1.027 ± 0.001	1.028 ± 0.001	+0.001	
National & international judo competitors (n = 9♂)	48 h (attempting rapid mass loss of 5% before a simulated judo competition [c])	Body mass (kg)	71.2 ± 9.3	67.7 ± 9.0	−3.5 kg (−4.9%)	[64]
		Urine specific gravity	1.014 ± 0.005	1.026 ± 0.003	+0.012	
Taekwondo, boxing and wrestling; national championship competitors (n = 244♂, 101♀)	N/A (one assessment, during an official event weigh-in)	Body mass (kg)	NR	♂, 74.1 ± 15.1 ♀, 57.1 ± 8.9	NR	[65]
		Urine specific gravity	NR	♂ and ♀, 1.027 [d]	NR	
		Rating of Thirst [e]	NR	♂ and ♀, 3.4 [d]	NR	

Notes: NR, data not reported; N/A, not applicable. [a] The various methods that athletes use to "make weight" are described in the Discussion section; [b] Relative to the PRE value (column 3); [c] Time of day was controlled; [d] Median values were reported with no standard deviation; [e] Described in Table 1, footnote [b].

Table 3 Change of Body Mass, Urine Specific Gravity, Thirst, and Serum Sodium Concentrations of Two Ultraendurance Road Cyclists (Columns 2 and 3) Who Experienced Exertional Hyponatremia

Measurements	Hyponatremic Male Cyclist A [a,b,c]	Hyponatremic Male Cyclist B [a,b,c]	Comparison Group (n = 31♂) [b,c]
Total fluid intake (volume/total ride time)	13.7 L/8.9 h [d]	14.7 L/10.6 h [d]	5.9 ± 2.4 L/9.0 ± 1.1 h
Body mass, pre-ride (kg)	72.0	77.5	85.4 ± 13.1
Body mass change during the event (kg)	+3.1 [d]	+0.1	−1.2 ± 1.9 kg
Body mass change during the event (%)	+4.3 [d]	+0.1	−1.3 ± 2.2
Urine specific gravity (pre-ride) [e]	1.003 [d]	1.005	1.019 ± 0.007
Urine specific gravity (post-ride) [e]	1.003 [d]	1.010	1.023 ± 0.007
Subjective thirst rating (pre-ride) [f]	2	1	2 ± 1
Subjective thirst rating (post-ride) [f]	2 [d]	2 [d]	5 ± 2
Serum sodium concentration (pre-ride, mmol/L) [g]	141	141	141 ± 1
Serum sodium concentration (post-ride, mmol/L) [g]	130 [d]	130 [d]	141 ± 3

Notes: Data from Armstrong.[27] [a] Mild exertional hyponatremia (ie, serum sodium concentration of 130–135 mmol/L) involves nonspecific symptoms such as nausea and lightheadedness. Severe symptomatic hyponatremia (<125 mmol/L) may involve vomiting, headache, confusion, pulmonary edema, frothy sputum, dyspnea, seizure, cerebral swelling, or death[66]; [b] The range of serum sodium concentration in healthy adults is 136–145 mmol/L[67]; [c] Cyclist ages (y) were 31 (A), 39 (B), 37 ± 6 (comparison group); [d] This value is outside the statistical 95% confidence interval of the control group who completed the event with normal serum sodium levels (column 4); [e] Measured from a single urine sample using a hand-held refractometer; [f] See Table 1, footnote [b]; [g] Measured in triplicate using a laboratory benchtop sodium analyzer.

restriction, a 30-min unrestricted water intake, and a 24-h ad libitum water rehydration. It is noteworthy that the average changes of body mass, urine specific gravity, and rating of thirst in Table 5 (ie, involving no exercise, column 4) are greater than many of the changes that are reported in Tables 1–3 which involved exercise.

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Table 4 A Comparison of Morning and Afternoon Body Mass, Urine Specific Gravity, and Thirst Values[a] for 24 healthy, Young Adults[b] Who Conducted Routine Daily Activities (Free Living) Including Eating, Drinking, and Recreational exercise

Criterion Biomarkers	First Morning Measurement	Afternoon (1400–1600 h)
Body mass (kg)	74.91 ± 16.08	75.13 ± 16.00
Urine specific gravity	1.019 ± 0.008	1.014 ± 0.008
Subjective rating of thirst [c]	5 ± 2	3 ± 2

Notes: Data from these studies.[69,70] [a] All values represent a 3-day mean (± SD, n = 24) with no experimental intervention except laboratory visits for measurements; [b] 12 men (age, 21 ± 2 y; body mass, 81.0 ± 15.9 kg) and 12 women (age, 22 ± 3 y; body mass, 68.8 ± 15.2 kg); [c], see Table 1, footnote [b] for details.

Table 5 The Effects of Water Restriction and Rehydration on Body Mass, Urine Specific Gravity, and Thirst During Routine Daily Activities. These Measurements Were Obtained During Five Laboratory Visits on Three Consecutive Days (Columns 2–6). At All Other Times, These 14 healthy Young Men[a] Were Free Living and Refrained From Exercise. On Days 1 and 2 (Columns 2–4), They Consumed No Water and Ate Only Dry Food Items for 24 h. During the 30-min Unrestricted Water Intake Period (Day 2, Column 4 to 5), Participants Drank as Much Water as Desired[b], Then Consumed Water and Food Ad Libitum for 24 h (Columns 5 and 6)

Measurement	Day 1, 24 h Water Restriction Begins in a Euhydrated State [c] (07:30h)	Day 1, after 8.5h of Water Restriction (16:00h)	Day 2, 24 h of Water Restriction Ends (07:30h) and 30 min of Unrestricted Water Intake Begins	Day 2, 30 min of Unrestricted Water Intake Ends [b] (08:00h) and 24 h ad libitum Water Rehydration Begins	Day 3, 24 h of ad libitum Water Rehydration Ends (08:00h)
Body mass (kg)	80.11 ± 10.58	79.26 ± 10.63	78.43 ± 10.52	79.63 ± 10.79	79.62 ± 10.48
Body mass change (%) [d]	-	−1.1 ± 0.5	−2.1 ± 0.5	−0.6 ± 0.7	−0.6 ± 0.6
Urine specific gravity	1.020 ± 0.007	1.028 ± 0.003	1.030 ± 0.008	1.029 ± 0.003	1.021 ± 0.008
Thirst rating [e]	55 ± 14	84 ± 13	88 ± 14	15 ± 10	56 ± 26

Notes: Data from these studies.[23,68] [a] Mean ± SD age, 23 ± 3y; [b] 1.43 ± 0.42 L of water was consumed in 30 min; [c] On the evening prior to this, participants consumed 500 mL of water in addition to their usual daily water intake, to increase the likelihood that they would arrive on Day 1 in a euhydrated state; [d] Relative to the euhydrated body mass in column 2; [e] Participants marked a visual analog scale (100 mm straight line flanked by "not at all" on the left side and "very" on the right) in response to the question "How thirsty are you?"

Figure 2 provides a visual summary of the hydration biomarker data (group averages) contained in Tables 1 and 5. As such, it illustrates net body water loss during athletic competition or training, as well as water restriction during daily activities that include no exercise. All thirst ratings and urine specific gravity values in Figure 2 increased when a net body water loss occurred (ie, body mass decreased). Figure 3 further illustrates the association among the criterion biomarker data (group averages) from the research studies presented in Tables 1–5.

Discussion

The evidence gathered by the present narrative review illustrates a wide range of hydration biomarker changes (ie, shown as standard deviations from the mean) which men and women experience during competition, training, and routine daily activities. Although not within the scope of the present study, from the assessed literature it is evident that this sizeable variability results from interactions of (a) sport-specific exercise mode, duration, and intensity; (b) individual differences of heat acclimatization status, fluid-electrolyte losses in sweat, physical training history, personal knowledge or beliefs

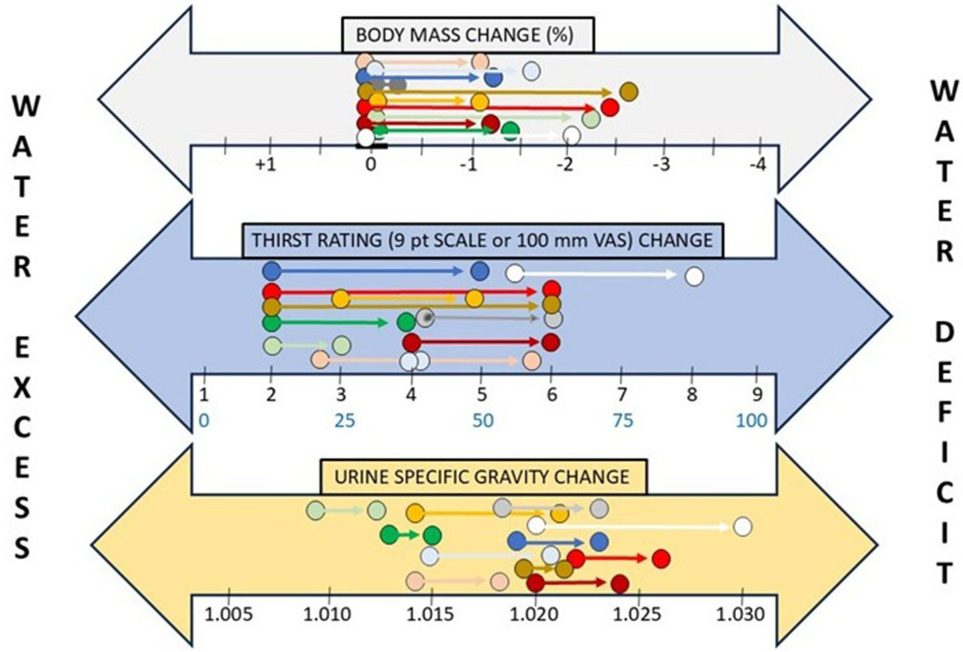

Figure 2 A visual summary of body mass, thirst rating, and urine specific gravity changes due to net body water loss during various activities. The 10 color-coded symbols represent the athletic competitions and training sessions described in Table 1. White symbols denote the 24-h period of water restriction during routine daily activities (n = 14) with no exercise, as described in Table 5 (columns 2 to 4). All symbols represent group averages (range, n = 6–57). Abbreviation: VAS, visual analog scale.

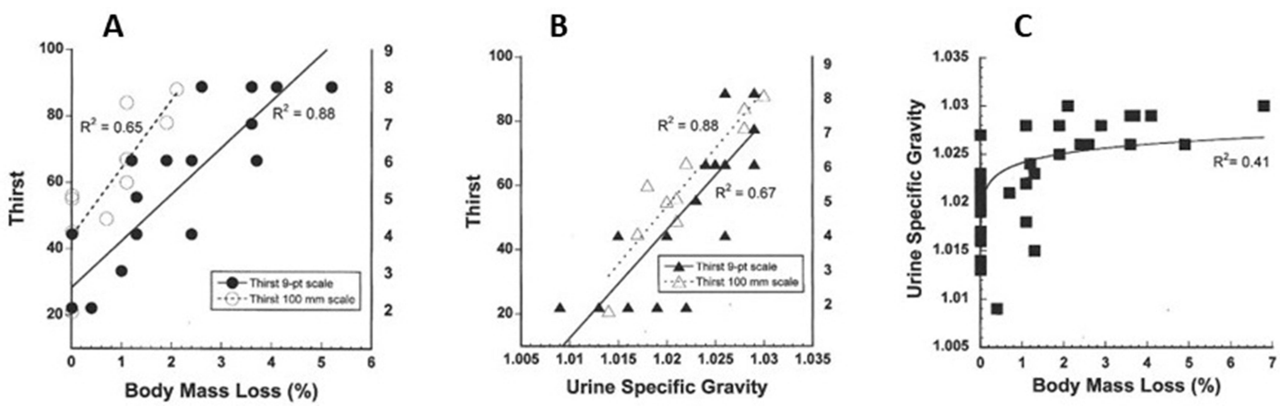

Figure 3 Relationships among the three hydration-relevant variables of this review: thirst, body mass loss, and urine specific gravity. Data points are mean values from the studies cited in Tables 1–5. Test participants rated thirst using either a 100-mm visual analog scale (left vertical axis) or a 9-point category scale (right vertical axis) in panels (**A**) and (**B**). Percent female sex: panel (**A**), 21%, panel (**B**), 8%, panel (**C**), 8%.

about rehydration during exercise; (c) intentional water loss by athletes who attempt to "make weight"; (d) gear or clothing insulation; and (e) environmental conditions.[31,51–54,71,72] This complexity and variability make it difficult to accurately predict in advance the fluid deficit or excess which any athlete might encounter during training or competition.[19,42,73,74] Thus, investigators and professional organizations recommend creating an individualized plan for each athlete.[3,4,19,30,34,56,73,75–77] However, previous investigations have not succeeded in providing practical, individualized hydration guidelines for athletes,[76] few inventories of hydration biomarker reference values have been published, and none of those studies examined the hydration biomarker responses of athletes during training, competition, overhydration, or purposeful weight loss for multiple sports[76,78–80] as are presented in Tables 1–3. Also, in most publications, a single hydration biomarker measurement (eg, urine specific gravity of 1.020) or a narrow range of values (eg, body mass loss of 3–4%) represents the threshold of detrimental effects for all athletes.[1,4,46,81–83] This approach does not take into account the large variability of hydration biomarker values shown in Tables 1–5.

Optimal IHPs incorporate biomarkers that are easy-to-use, field expedient, noninvasive, safe, portable, and inexpensive.[3,4,30,34,75,77] In view of these criteria, several hydration biomarkers were initially considered for inclusion in the present review,[34,37,39,84] including clinical assessment methods.[35] The following five points influenced our decision to employ three hydration biomarkers: body mass change, urine specific gravity, and subjective rating of thirst. First, the 2022 consensus statement of the International Olympic Committee Medical and Scientific Commission recommended that athletes monitor their body weight, urine specific gravity (or urine color), and thirst during periods of training or competing in hot environments.[82] Second, an evaluation of 13 hydration assessment methods determined that body mass change, urine specific gravity, and rating of thirst were among the top five most suitable field techniques;[34] the criteria for this finding were cost and time of analysis, technical expertise required, portability, and likelihood of an adverse event. Third, acute body mass change is recognized as the simplest and most accurate index of hydration status when serial measurements are collected in close proximity (eg, pre- and post-exercise, ≤ 4h) and when corrected for the mass of urine excreted and fluid consumed during the activity.[4,34,85–88] Fourth, human body water balance primarily depends on two parameters: thirst that influences input, and urine excretion that determines output. When a deficit or excess of total body water exists, the kidneys act to restore euhydration. As a result, a change of urine concentration (eg, specific gravity) can distinguish a net loss or gain of body water (Figure 2), discriminate between euhydration and dehydration,[4,27,89,90] and determine whether daily total water intake is adequate.[68,91–93] Fifth, measurements of body mass, urine specific gravity, and thirst each have limitations when they are employed alone to assess hydration state, due to factors such as time of day, internal circadian rhythms, first morning hydration state, and dietary osmolar load.[3,94–96] For example, consumption of a large bolus of water or a high protein diet may alter urine specific gravity acutely.[30,97,98] Also, the intensity of thirst may be difficult to replicate consistently on a rating scale due to the interactions of numerous internal physiologic (eg, plasma osmolality and volume, oropharyngeal sensations) and external (eg, fluid characteristics, learned preferences, air temperature) influencing factors which are integrated by the brain.[32,33,59,94–106] Therefore, we conclude that a single hydration assessment method (a) is not valid in all scenarios or for all individuals,[34–39] and (b) does not provide unequivocal evidence of fluid intake inadequacy.[31] However, research studies have shown that the combination of two hydration biomarkers makes identification of inadequate fluid intake or dehydration likely, and the combination of three indices makes this determination very likely.[31,55,70]

Hydration Biomarker Interrelationships

Figure 2 provides a visual summary of body mass changes (%), subjective thirst ratings, and urine specific gravity values from 12 studies which focused on outdoor athletic competitions or training sessions (Table 1), and 24-h water restriction during routine daily activities (Table 5). All symbols represent group means (n = 6–28) and illustrate consistent agreement among these three hydration indices, in that all thirst ratings increased and all urine specific gravity values increased when a net body water loss occurred (ie, body mass decreased).

Figure 3 illustrates the relationships of the three criterion biomarkers presented in Tables 1–5. The calculated Spearman's rho correlation coefficients of these relationships (R^2 = 0.41–0.88) are considered to be moderate (Panel C) and strong (panels A and B).[107] Thus, we propose the following theoretical interpretation of Figure 3 that arises from widely recognized physiological responses. Specifically, both urine concentration within the kidneys (ie, represented here by increased specific gravity) and the sensation of thirst are strongly influenced by a body water deficit (ie, elevated extracellular fluid concentration). These effects are regulated by the release of vasopressin (antidiuretic hormone) from the brain into the circulation,[108–111] in response to increased plasma concentration, decreased plasma volume, and/or reduced arterial blood pressure.[101,112] Additionally, thirst, urine concentration, and vasopressin release are influenced by oropharyngeal (ie, rear of the tongue, soft palate, and throat) nerve signals to the brain which rapidly reduce total fluid intake and modulate satiety,[113,114] often before blood volume–concentration–pressure changes occur. We believe that these interrelated responses account for the strong correlation shown in Figure 3.

Although an acute body mass change is recognized as the simplest and most accurate index of hydration status when serial measurements are collected in close proximity (as noted above), multiple factors influence the extent of this

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change.[115,116] To explore the possibility that body mass change may not be significantly correlated with urine specific gravity or thirst, we analyzed the data in Tables 1 and 2. Both the relationship between body mass change and urine specific gravity ($r = 0.50$, $p = 0.013$), as well as the relationship between body mass change and rating of thirst ($r = 0.68$, $p = 0.001$), were significantly correlated. The strength of these two relationships are interpreted as fair and moderately strong, respectively.[107,117]

The findings described in the three previous paragraphs demonstrate that our three criterion hydration biomarkers responded consistently when a body water deficit occurred; this suggests satisfactory internal validity. Two individual exceptions to this observation appear in Table 3, in the form of cyclists who experienced exertional hyponatremia during a 164-km summer ultraendurance event. Row 1 of Table 3 shows that the comparison group with normal serum sodium levels (column 4) consumed an average of 5.9 L of fluid during 9.0 h of cycling. In contrast, the hyponatremic cyclists A and B consumed 13.7 L/8.9 h and 14.7 L/10.6 h, respectively, which resulted in serum sodium concentrations of 130 mmol/L for both[27] – well below the range observed among healthy adults (136–145 mmol/L).[67] In terms of body mass, the comparison group lost 1.3%, cyclist A gained 4.3%, and cyclist B experienced virtually no change of body mass (+0.1%). This obvious difference among the two hyponatremic cyclists (ie, who had identical pre- and post-ride serum sodium values) likely resulted from a large difference in their sweat rates and the fact that cyclist B rode 1.7 h longer than cyclist A. It is noteworthy that both cyclists A and B exhibited post-ride urine specific gravities and thirst ratings that were well below the mean values of the comparison group (column 4). This illustrates an important concept. Due to the complex interactions of many factors, some cases of exertional hyponatremia involve body mass gain (ie, overhydration and water retention that exceeds sweat, urine, and respiratory water losses),[118,119] whereas other cases are associated with a large unreplaced sweat sodium loss and partially-replaced water loss.[120–122] Thus, the development of exertional hyponatremia in cyclists A and B (Table 3) and the responses of hydration biomarkers were idiosyncratic.[27]

Considerations for Developing an IHP

Previous publications describe (a) the negative effects which fluid–electrolyte imbalances can have on athletic performance, physiological functions, and health;[3,4,46,51] and (b) the importance of developing an IHP for each athlete,[123] as opposed to utilizing a single hydration biomarker value or a narrow range of values to indicate the threshold of detrimental effects for all athletes.[84,98] In its simplest form, an IHP involves measuring an athlete's sweat rate (described in the section titled "Body mass") and planning the appropriate volume and timing of fluid intake in view of the anticipated rehydration opportunities of the sport. More sophisticated IHP models take into account an athlete's tolerance to consuming a relatively large fluid volume,[41] the concentration of electrolytes in sweat (ie, sodium, chloride, potassium),[124,125] or the events that require sodium and carbohydrate in rehydration fluids.[51,122,126] An IHP that incorporates most or all of these factors increases the likelihood that an athlete will attain the desirable middle ground between underhydration and overhydration, thereby optimizing performance.

Interpreting Biomarker Data

The hydration biomarker data in Tables 1–5 are intended to be used concurrently with other information to interpret changes of hydration status. Because no single biomarker accurately indicates hydration status for all athletes, activities, and environments, and because different biomarkers sometimes provide conflicting information (ie, due to the dynamic complexity of human fluid–electrolyte regulation[29–33]), it is best to employ information from multiple sources to determine hydration status.[31–55] One common technique involves comparing an athlete's biomarker information to a single static value that represents the threshold of detrimental effects attributed to dehydration; in fact, most sport nutrition and human hydration publications[4,44–50] provide a single biomarker value (eg, urine specific gravity of 1.020) or a narrow range of values (eg, body mass loss of 3–4%) for all athletes, activities, and environments. As a second source of information, each athlete can maintain a personal diary of body weight, urine specific gravity, and thirst measurements, before and after exercise; with this data, he/she can monitor trends across days and weeks to develop personalized reference values representing usual body weight changes, urine specific gravities, and thirst ratings. This diary of past hydration experiences can then be compared to each new competition or daily training session. The biomarker data of the present review represents a third source of information. Tables 1–5 provide activity-specific values which can be utilized by athletes,

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coaches, clinicians, and physiologists as one source of information to interpret IHP effectiveness. Changes (pre- versus post-exercise) of an athlete's body mass, urine specific gravity, and thirst can be compared to the hydration biomarker averages in Tables 1–5, to determine if those changes are typical of that sport or activity; if dehydration, euhydration (ie, optimal body water balance), or overhydration exist; and the extent of body water loss or gain experienced (ie, departure from average values). Further, athletes and coaches who have not collected hydration biomarker data previously can refer to the values in Tables 1–5 for a general idea of what to expect when they begin measurements.

With regard to the practical application of data in Tables 2–5, we offer four additional observations. First, the various methods of making weight in combat sports (Table 2) all result in dehydration and loss of body mass. Thus, during the process of restoring body mass to the pre-exercise level, we recommend that measurements of our three criterion biomarkers be scheduled throughout the refeeding and rehydration process. Second, in cases of overhydration (Table 3), changes of biomarker values may differ from one athlete to the next, depending on the volume and rate of fluid intake, sweat rate, body size, duration of exercise, and other factors.[27] We recommend that a sports medicine physician be consulted if body mass increases and if urine specific gravity is unusually low post-exercise, suggesting retention of excess water; also refer to the section titled "Avoiding overhydration". Third, body mass tends to be lower in the morning, whereas first morning urine specific gravity and rating of thirst tend to be greater than midday and afternoon values, as shown in Table 4. If measurements are recorded at various times of the day, they may be confounded by water and food intake, voiding, exercise, and internal circadian rhythms.[95] Thus, we recommend day-to-day consistency in the time of measurements.[31,76] Fourth, as illustrated in Table 5, ordinary daily activities with no exercise can influence an athlete's body water balance. To ensure that she/he begins a competitive event or daily training session well-hydrated, morning measurements of the three criterion variables should guide pre-exercise fluid intake.

The following points present additional insights regarding the interpretation of biomarker data.

- To discover an athlete's typical patterns of fluid loss and fluid intake, several observations should be made in conjunction with training sessions and relevant field simulations of competitive events.
- Because our three criterion biomarkers reflect the responses of different organ systems, it is possible that one hydration index indicates a water excess whereas the other two indices suggest a water deficit. In this case, the majority indication should be utilized until another assessment is completed a few hours later.[124]
- When extreme or chronic biomarker changes are observed, consider possible causes and repeat measurements at regular intervals. If values do not return to pre-exercise levels within a reasonable time frame, consult a physician.

Body Mass

- During exercise lasting 0.5–4.0 h, body mass change is the most commonly used representation of body water loss or gain[36,39] because muscle mass and adipose tissue changes are negligible.
- We recommend using the same digital floor scale each time that body mass is measured. Many floor scales can be calibrated by following the manufacturer's instructions and loading the scale with objects of known mass. Identical clothing and footwear should be worn during each measurement. A digital floor scale that reads to ±100 g has a measurement resolution of ±0.1 L (eg, 100 mL out of a 42–47 L total body water volume).
- An athlete's sweat rate (ie, the volume of sweat produced per hour, expressed as L/h or qt/h) is determined by measuring pre-exercise nude body mass and exercising for 60 min (ie, in an environment, at an exercise intensity, and wearing clothing/equipment that simulates a future event). After exercise, nude post-exercise body mass, with sweat wiped from the skin, is subtracted from the pre-exercise body mass and corrected for fluid consumed and urine eliminated, if any.[41,51,124] Additional details regarding the calculation of sweat rate, plus the methods for measuring sweat electrolyte losses (eg, sodium, potassium), appear elsewhere.[41,124]
- Sweat electrolyte losses become problematic during events lasting more than 4 h (ie, due to an increased risk of exertional hyponatremia) or across consecutive days of heavy sweating with inadequate dietary water and sodium replacement.[24,41,51]
- To assess the day-to-day change of body mass, measurements should be compared to the baseline body mass for that individual. To determine this baseline, measure morning body mass on 3–5 consecutive days.[85] The median (middle) or average body mass serves as a meaningful baseline for that individual.[124] If the body mass value on the

morning after an endurance event is notably less or greater than baseline, fluid intake should be adjusted accordingly (ie, avoiding overconsumption and underconsumption) for 24–48 h.[75,127]

- Two other considerations are relevant. First, if dietary "carbohydrate loading" is employed during the days prior to competition, the baseline body mass may increase (0.5–1.5 kg) because water is stored with glycogen in skeletal muscles. Second, body mass measurements may not be valid after an event lasting 7–24 h because cellular water is generated during metabolic reactions, and skeletal muscle or adipose tissue is degraded.[51,115,128,129]

Urine Specific Gravity

When a total body water deficit exists, the kidneys retain water by concentrating urine and decreasing urine volume; in contrast, when excess fluid has been consumed and retained, a larger volume of dilute urine is produced. These changes (ie, dehydration or fluid overload) can be detected by observing urine samples.

- Urine specific gravity is recommended as a practical and valid biomarker for identifying suboptimal fluid intake or underhydration by professional sports medicine organizations,[3,4,46] physiologists, and researchers.[6,76,89,97,130–132]
- Urine specific gravity (see Tables 1–5, Figures 2 and 3) is measured quickly and accurately with a refractometer.[75,133] This instrument is relatively inexpensive, simple to use, and is available from online retail platforms as a handheld device which can be calibrated before use.
- An euhydrated urine specific gravity baseline value (ie, usually between 1.015 and 1.025[26,27]) should be determined for each athlete, using a method similar to the one described above for body weight. Changes from this baseline value will assist the interpretation of hydration status.
- Hydration assessment via urine specific gravity has limitations when used alone,[90,98,134] as do all hydration biomarkers.
- Many athletes consume nutritional supplements to gain a performance edge or health benefit.[135–138] When consumed in the manufacturer's recommended dosage, supplements such as vitamin C, beetroot, and riboflavin may or may not alter urine color.[139,140] However, even if they visibly alter urine color, it is unlikely that nutritional supplements will measurably influence urine specific gravity because the mass and osmolar content of nutritional supplements is small in comparison to the total osmolar load of the food items in an athlete's daily diet.[30]
- During normal daily activities, men may[78,79,141] or may not[69,70] exhibit a greater urine specific gravity than women.
- An analysis of data from the National Health and Nutrition Examination Survey (NHANES; n = 3,634) indicated that urine specific gravity is influenced by body size and body composition.[142] Thus, athletes who have a large lean body mass or body mass index can be expected to have greater urine specific gravity values than their smaller counterparts.
- If an athlete consumes a large volume of pure water or dilute beverage rapidly (eg, 1.4 L in 30 minutes), urine specific gravity decreases (eg, < 1.010) in both well-hydrated and dehydrated athletes as a defense against fluid overload.[97] In contrast, if the same volume of water or dilute fluid is consumed gradually and in small aliquots, the change of urine specific gravity will be minor.[30,115,119] The sensation of thirst exhibits a parallel phenomenon.

Rating of Thirst

As noted above, thirst is a sensation that regulates total body water and the concentration of body fluids. Coordinated by the brain, thirst responds in concert with renal responses to correct fluid and electrolyte perturbations. Figure 3 illustrates the relationships between thirst, urine specific gravity, and body mass loss. In particular, panel A supports our recommendation to assess subjective ratings of thirst.

- In research studies involving a variety of activities, thirst ratings have consistently identified an existing body water deficit. See Figure 2.
- Thirst is initially sensed when a body mass loss of 1–2% occurs during exercise-heat stress,[11,32] or when a 0.5% body mass loss occurs during routine daily activities involving no exercise,[23] and intensifies as the body water deficit increases.

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- Research has shown that the morning sensation of thirst upon waking is a reliable indicator of hydration status.[76,143] However, an intense morning sensation of thirst may not affect body mass, total water intake, or hydration status later in the day.[69]
- We recommend measuring thirst with a 9-point intensity rating scale[63] because of its simplicity. This scale offers the following options: 1, not thirsty at all; 3, a little thirsty; 5, moderately thirsty; 7, very thirsty; and 9, very very thirsty. See Tables 1–4 and Figure 3.
- An euhydrated baseline thirst rating should be determined for each athlete, using a method similar to the one described above for body weight. Changes from this baseline value will assist the interpretation of hydration status.
- Field studies have reported that thirst was not correlated with the hydration status of youth campers[144] and high school football players.[145] This may be due to an age-related difference of thirst (ie, influenced by puberty and maturation). Alternatively, these observations may be due to the difficulty of controlling pre-exercise hydration state or fluid intake throughout the day, in a field setting. This matter requires further investigation to determine its relevance to the thirst responses of young athletes.

Strategies for Drinking During Exercise

- An important component of each IHP is the amount of fluid which an athlete can gain access to during training or competition.[41] If an athlete has unrestricted access, consuming the appropriate amount of fluid is relatively easy. However, the rules of many sporting events (eg, tennis) do not allow continuous access to fluids; this challenges the athlete to appropriately time his or her fluid intake. Also, if the athlete is participating in an endurance running event, the number of aid stations are predetermined. Thus, it is essential for the athlete to determine his/her sweat rate (described above) and consider the total exercise time, to calculate how much he or she should consume at each station.
- When developing an approach to fluid intake during prolonged or endurance events, athletes have five options: (1) drink only when thirst is sensed, (2) drink whenever and in whatever volume is desired (ie, ad libitum), (3) drink according to an IHP, (4) drink nothing during exercise, and (5) drink as much as possible, in excess of thirst. A detailed comparison of these options, including pros and cons, appears elsewhere.[51] To our knowledge, no professional sports medicine or sport nutrition organization recommends options 4 and 5. The present authors support option 3.
- A controlled, single-blinded research study[146] reported that prolonged ad libitum fluid replacement (option 2 above), after a 110-min intermittent running session, left a small degree of hypohydration at 20 h post-exercise. Consistent with this finding, endurance athletes consistently replace ≤ 50% of sweat losses when allowed to consume liquids ad libitum during exercise.[147–149] These publications support the development and application of an IHP for athletes (option 3 above).
- In sports where athletes have few, defined opportunities to drink (eg, soccer, field hockey, rugby), it is essential that athletes begin competition well-hydrated but not overhydrated. The values of body mass change, urine specific gravity, and subjective rating of thirst in Tables 1–5 can be employed to interpret an athlete's hydration status prior to an event.
- Utilizing the reference values in Tables 1–5 to develop an IHP, each athlete can seek a hydration middle ground between dehydration and overhydration that allows him/her to optimize physical performance and reduce the risk of illness.

Avoiding Overhydration

As discussed above, the development of exertional hyponatremia and the changes of hydration biomarkers in Table 3 are idiosyncratic.[27] We therefore believe that creating an IHP is the most straightforward pre-event action that athletes can take to avoid excessive fluid intake. This involves measuring personal sweat rate (L/h) and considering the event duration (h), to calculate a rate of fluid intake (L/h) that results in no increase of body mass (ie, indicating retention of excess fluid).

- Body mass, measured before and after exercise with a digital floor scale, informs post-exercise fluid consumption.[3]
- A low specific gravity value (eg, less than 1.010) or pale yellow urine color (see below) in multiple consecutive urine samples typically indicates overhydration (ie, the kidneys are releasing excess body water) and suggests that fluid intake should be curtailed and monitored until specific gravity values moderate.

- In field settings, when a refractometer or floor scale is not available, urine color can be used to estimate hydration status and the adequacy of daily water intake.[89,97,150,151] This field expedient technique is accomplished in outdoor daylight or a well-lit room by holding urine samples against a white background and rating them as whole numbers, after comparison to a previously validated chart (scale colors ranging from 1 [lightest] to 8 [darkest]).[89,97] This chart, including interpretative guidelines, can be requested from the first author via Email (see title page). Two important precautionary notes are in order. First, computer screens and printed pages often produce copies of online color charts that have invalid colors. Second, numerous urine color charts can be found online but few have been validated in human research studies.
- Before exercise, a low urine specific gravity (eg, 1.003 or 1.005; see Table 3, row 5) increases the risk of developing exertional hyponatremia.[26,27]
- During exercise, being alert for the signs and symptoms of exertional hyponatremia provides additional protection. For example, mild exertional hyponatremia exhibits nonspecific symptoms (eg, nausea, lightheadedness, headache), whereas severe symptomatic hyponatremia may involve vomiting, altered mental status, frothy sputum, collapse, seizure, or coma.[3,66]
- Two previous analyses of triathlete and endurance runner data[25,51] showed that those who consumed fluids at a rate < 700 mL/h had a decreased risk of symptomatic exertional hyponatremia (serum sodium < 130 mmol/L). This 700 mL/h threshold is consistent with the fluid intake recommendations of the International Marathon Medical Directors Association,[152] the American College of Sports Medicine,[4] and a mathematical model that was designed to clarify the etiology of exertional hyponatremia.[24]

Weight Category Sports

Various methods are employed to "make weight" in rowing, powerlifting, body building, and combat sports (ie, boxing, wrestling, taekwondo, judo, mixed martial arts). These methods include fasting, fluid restriction, exercise-induced sweating, avoiding foods with high carbohydrate content (ie, to avoid water retention in muscle and liver tissues), exercise-induced sweating, sauna, hot salt baths, vomiting, diet pills, laxatives, and diuretics.[71,72,153–158]

- Each of these weight loss methods results in a unique combination of water, fat, and/or lean tissue loss; also, the effects of each on urine specific gravity and thirst are unique.
- The majority of purposeful weight loss methods involve a body water deficit, increased urine specific gravity, and increased thirst. Water loading (ie, consumption of large fluid volumes for days, followed by sudden fluid restriction on the day before weigh-in) is an exception, however this practice increases the risk of fluid overload hyponatremia (see above).
- The rapid body mass losses of rowing and combat sport competitors average 3.2–5.2% in 3–24 h.[159] Also see Table 2.
- The short-term body mass reductions (3–5 d) among boxing, wrestling, and taekwondo athletes range from 3.0–6.2%.[159]
- Gradual, long-term weight management regimens (2–8 wk) of combat sport athletes reportedly result in average body mass losses up to 18.1%.[159]
- The time that elapses between weigh-in and competition varies among sports, and affects the ability of athletes to recover from mass loss. Sports that offer a long recovery time (eg, up to 32 h) between the weigh-in and competition allow athletes to be well-hydrated and well-fueled. However, these sports also support extreme body mass manipulation, as evidenced by an average mass recovery of 9.1–10.1% by mixed martial arts competitors,[160] whose recovery values ranged up to 20%.[159]
- During the week following competition, an investigation of Australian Olympic combat sports[161] revealed that athletes regained considerable body weight (eg, boxing, 4.1%; judo, 3.6%; taekwondo, 4.6%; and wrestling, 4.8% of their baseline body mass).
- We recommend downloading a copy of the 2021 American College of Sports Medicine consensus statement which focuses on weight-category sports.[159] This document contains a wealth of information regarding the benefits and disadvantages of weight-making practices, pre-event weigh-in procedures, opportunities for recovery after weigh-in, sport rule changes to minimize potential harmful effects of making weight, and recommendations for safer weight-making practices in various sports.

Routine Daily Activities

- During ordinary daily activities, the average body mass may be lower in the morning (whereas urine specific gravity and thirst values tend to be greater) than during afternoon hours (Table 4). However, because exceptions have been reported,[69] the morning body mass of each athlete should be recorded in a personal diary each day, to determine his/her unique responses.
- Most humans do not experience severe dehydration (> 5% body mass loss) during routine daily activities but may reach a state of mild dehydration (1–2% of body mass lost as water) multiple times each week.[30] For example, an average body mass loss of 1.1% was observed in healthy young men after only 8.5 h of water restriction (Table 5).
- For reasons that have not been clarified, some individuals habitually consume little water each day.[30] These low volume drinkers (plain water + beverages + food moisture < 1.5 L/24 h) represent 25–33% of all adults in the United States and Europe.[162–164] This 1.5 L volume is considerably less than the Adequate Intakes for water recommended by the European Food Safety Authority[165] and the US National Academy of Medicine[166] for men (2.5, 3.7 L/d) and for women (2.0, 2.7 L/d).
- A 2024 review paper[167] reported that chronic low volume drinking behavior, and/or urine biomarkers that signal chronic dehydration, are strongly associated with two disease states: type 2 diabetes and kidney stones.
- The four preceding observations emphasize that hydration practices during routine daily activities are an important aspect of an athlete's hydration state. To ensure that she/he begins a competitive event or training session well-hydrated, the pre-exercise biomarker values in Tables 1–4 can be utilized to interpret an athlete's hydration status prior to exercise.

Summary

The hydration biomarker changes in Tables 1–5 provide reference values that can be compared to an athlete's body weight, urine specific gravity, and thirst sensation. These reference values are intended to be used as one component of a comprehensive IHP. Such comparisons enhance the interpretation of both pre- and post-exercise measurements uniquely, by providing a window into the past experiences of athletes during outdoor events, weight category sports, training sessions, and routine daily activities. This repository of sport-relevant hydration biomarker data is unique in the extant literature because it does not rely on single threshold values (ie, one value fits all). We propose that consistent use of these reference values, as part of a multi-faceted IHP, will clarify the extent of dehydration or overhydration, guide rehydration efforts, and optimize subsequent exercise performance, recovery, and health.

Author Contributions

All authors made a significant contribution to the work reported, whether that is in the conception, study design, execution, acquisition of data, analysis and interpretation, or in all these areas; took part in drafting, revising, or critically reviewing the article; gave final approval of the version to be published; have agreed on the journal to which the article has been submitted; and agree to be accountable for all aspects of the work.

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References

1. Collins J, Maughan RJ, Gleeson M, et al. UEFA expert group statement on nutrition in elite football. Current evidence to inform practical recommendations and guide future research. *Br J Sports Med*. 2021;55(8):416–442. doi:10.1136/bjsports-2019-101961
2. Kenefick RW. Drinking strategies: planned drinking versus drinking to thirst. *Sports Med*. 2018;48(Suppl 1):31–37. doi:10.1007/s40279-017-0844-6
3. McDermott BP, Anderson SA, Armstrong LE, et al. National Athletic Trainers' Association position statement: fluid replacement for the physically active. *J Athl Train*. 2017;52(9):877–895. doi:10.4085/1062-6050-52.9.02
4. Sawka MN, Burke LM, Eichner ER, et al. American college of sports medicine position stand. Exercise and fluid replacement. *Med Sci Sports Exerc*. 2007;39(2):377–390. doi:10.1249/mss.0b013e31802ca597
5. Armstrong LE, Hubbard RW, Szlyk PC, Sils IV, Kraemer WJ. Heat intolerance, heat exhaustion monitored: a case report. *Aviat Space Environ Med*. 1988;59(3):262–266.
6. Donoghue AM, Sinclair MJ, Bates GP. Heat exhaustion in a deep underground metalliferous mine. *Occup Environ Med*. 2000;57(3):165–174. doi:10.1136/oem.57.3.165
7. Gaffin SL, Hubbard RW. Pathophysiology of heatstroke. In: Pandolf KB, Burr RE, editors. *Medical Aspects of Harsh Environments*. Washington DC: U.S. Army Office of the Surgeon General; 2001:161–208.
8. Kenefick RW, Sawka MN. Heat exhaustion and dehydration as causes of marathon collapse. *Sports Med*. 2007;37(4–5):378–381. doi:10.2165/00007256-200737040-00027
9. Sawka MN, Young AJ, Latzka WA, Neufer PD, Quigley MD, Pandolf KB. Human tolerance to heat strain during exercise: influence of hydration. *J Appl Physiol*. 1992;73(1):368–375. doi:10.1152/jappl.1992.73.1.368
10. Judelson DA, Maresh CM, Anderson JM, et al. Hydration and muscular performance: does fluid balance affect strength, power and high-intensity endurance? *Sports Med*. 2007;37(10):907–921. doi:10.2165/00007256-200737100-00006
11. Adolph EF. Signs and symptoms of desert dehydration. In: Adolph EF, editor. *Physiology of Man in the Desert*. Cummings Park, MA: Interscience Publishers, Inc.; 1947:226–240.
12. Armstrong LE. Heat exhaustion. In: Adams WM, Jardine J, editors. *Exertional Heat Illness: A Clinical and Evidence-Based Guide*. Springer Nature; 2020:81–115.
13. Marriott HL. Water and salt depletion. *Br Med J*. 1942;2:285–290.
14. Armstrong LE, Hubbard RW, Jones BH, Daniels JT. Preparing Alberto Salazar for the heat of the 1984 Olympic marathon. *Physician Sportsmed*. 1986;14(3):73–81. doi:10.1080/00913847.1986.11709011
15. Bergeron MF. Heat cramps: fluid and electrolyte challenges during tennis in the heat. *J Sci Med Sport*. 2003;6(1):19–27. doi:10.1016/s1440-2440(03)80005-1
16. Speedy DB, Noakes TD, Rogers IR, et al. Hyponatremia in ultradistance triathletes. *Med Sci Sports Exer*. 1999;31(6):809–815. doi:10.1097/00005768-199906000-00008
17. Hahn RG, Waldreus N. An aggregate urine analysis tool to detect acute dehydration. *Int J Sport Nutr Exerc Metab*. 2013;23(4):303–311. doi:10.1123/ijsnem.23.4.303
18. Shirreffs SM, Aragon-Vargas LF, Chamorro M, Maughan RJ, Serratosa L, Zachwieja JJ. The sweating response of elite professional soccer players to training in the heat. *Int J Sports Med*. 2005;26(2):90–95. doi:10.1055/s-2004-821112
19. Shirreffs SM, Sawka MN, Stone M. Water and electrolyte needs for football training and match-play. *J Sports Sci*. 2006;24(7):699–707. doi:10.1080/02640410500482677
20. Yeargin SW, Casa DJ, Armstrong LE, et al. Heat acclimatization and hydration status of American football players during initial summer workouts. *J Strength Cond Res*. 2006;20(3):463–470. doi:10.1519/20596.1
21. Ceylan B, Barley OR, Balci SS. Changes in body mass and hydration status in judo athletes before and after a top-level competition: a descriptive case study. *Physician Sportsmed*. 2023;51(3):228–233. doi:10.1080/00913847.2022.2026200
22. Sommerfield LM, McAnulty SR, McBride JM, et al. Validity of urine specific gravity when compared with plasma osmolality as a measure of hydration status in male and female NCAA collegiate athletes. *J Strength Cond Res*. 2016;30(8):2219–2225. doi:10.1519/JSC.0000000000001313
23. Armstrong LE, Giersch GEW, Colburn AT, et al. Progression of human subjective perceptions during euhydration, mild dehydration, and drinking. *Physiol Behav*. 2021;229:article113211. doi:10.1016/j.physbeh.2020.113211
24. Montain SJ, Cheuvront SN, Sawka MN. Exercise associated hyponatraemia: quantitative analysis to understand the aetiology. *Br J Sports Med*. 2006;40(2):98–105. doi:10.1136/bjsm.2005.018481
25. Armstrong LE. Exertional hyponatremia. In: Armstrong LE, editor. *Exertional Heat Illnesses*. Champaign, IL: Human Kinetics; 2003:103–136.
26. Armstrong LE, Curtis WC, Hubbard RW, Francesconi RP, Moore R, Askew EW. Symptomatic hyponatremia during prolonged exercise in heat. *Med Sci Sports Exerc*. 1993;25(5):543–549. doi:10.1249/00005768-199305000-00003
27. Armstrong LE, Lee EC, Casa DJ, et al. Exertional hyponatremia and serum sodium change during ultraendurance cycling. *Int J Sport Nutr Exerc Metab*. 2017;27(2):139–147. doi:10.1123/ijsnem.2016-0135
28. Gardner JW. Death by water intoxication. *Mil Med*. 2002;167(5):432–434. doi:10.1093/milmed/167.5.432
29. Armstrong LE, Johnson EC. Water intake, water balance, and the elusive daily water requirement. *Nutrients*. 2018;10(12):article1928. doi:10.3390/nu10121928
30. Armstrong LE, Munoz CX, Armstrong EM. Distinguishing low and high water consumers—a paradigm of disease risk. *Nutrients*. 2020;12(3):article858. doi:10.3390/nu12030858
31. Cheuvront SN, Kenefick RW. Am I drinking enough? Yes, no, and maybe. *J Am Coll Nutr*. 2016;35(2):185–192. doi:10.1080/07315724.2015.1067872
32. Greenleaf JE. Problem: thirst, drinking behavior, and involuntary dehydration. *Med Sci Sports Exer*. 1992;24(6):645–656. doi:10.1249/00005768-199206000-00007
33. Thornton SN. Thirst and hydration: physiology and consequences of dysfunction. *Physiol Behav*. 2010;100(1):15–21. doi:10.1016/j.physbeh.2010.02.026

34. Armstrong LE. Assessing hydration status: the elusive gold standard. *J Am Coll Nutr*. 2007;26(Suppl 5):575S–584S. doi:10.1080/07315724.2007.10719661
35. Armstrong LE, Kavouras SA, Walsh NP, Roberts WO. Diagnosing dehydration? Blend evidence with clinical observations. *Curr Opin Clin Nutr Metab Care*. 2016;19(6):434–438. doi:10.1097/MCO.0000000000000320
36. Kavouras SA. Assessing hydration status. *Curr Opin Clin Nutr Metab Care*. 2002;5(5):519–524. doi:10.1097/00075197-200209000-00010
37. Kavouras SA. Hydration, dehydration, underhydration, optimal hydration: are we barking up the wrong tree? *Eur J Nutr*. 2019;58(2):471–473. doi:10.1007/s00394-018-01889-z
38. Lacey J, Corbett J, Forni L, et al. A multidisciplinary consensus on dehydration: definitions, diagnostic methods and clinical implications. *Ann Med*. 2019;51(3–4):232–251. doi:10.1080/07853890.2019.1628352
39. Shirreffs S. Markers of hydration status. *J Sports Med Phys Fitness*. 2000;40(1):80–84.
40. Ayotte D Jr, Corcoran MP. Individualized hydration plans improve performance outcomes for collegiate athletes engaging in in-season training. *J Int Soc Sports Nutr*. 2018;15(1):article27. doi:10.1186/s12970-018-0230-2
41. Casa DJ, Armstrong LE, Ganio MS, Kavouras SA, Wingo JE. Hydration for High-Level Athletes. In: Rawson ES, Volpe SL, editors. *Nutrition for Elite Athletes*. Boca Raton, FL: CRC Press; 2016:249–274.
42. Casa DJ, Cheuvront SN, Galloway SD, Shirreffs SM. Fluid Needs for training, competition, and recovery in track-and-field athletes. *Int J Sport Nutr Exerc Metab*. 2019;29(2):175–180. doi:10.1123/ijsnem.2018-0374
43. Muñoz CX, Johnson EC. Hydration for Athletic Performance. In: Bagchi D, Nair S, Sen CK, editors. *Nutrition and Enhanced Sports Performance*. Philadelphia, PA: Elsevier; 2019:533–543.
44. Armstrong LE, Casa DJ, Millard-Stafford M, Moran DS, Pyne SW, Roberts WO. American college of sports medicine position stand. Exertional heat illness during training and competition. *Med Sci Sports Exerc*. 2007;39(3):556–572. doi:10.1249/MSS.0b013e31802fa199
45. Bartok C, Schoeller DA, Sullivan JC, Clark RR, Landry GL. Hydration testing in collegiate wrestlers undergoing hypertonic dehydration. *Med Sci Sports Exer*. 2004;36(3):510–517. doi:10.1249/01.mss.0000117164.25986.f6
46. Casa DJ, Armstrong LE, Hillman SK, et al. National athletic trainers' association position statement: fluid replacement for athletes. *J Athl Train*. 2000;35(2):212–224.
47. Casa DJ, Clarkson PM, Roberts WO. American College of sports medicine roundtable on hydration and physical activity: consensus statements. *Curr Sports Med Rep*. 2005;4(3):115–127. doi:10.1097/01.csmr.0000306194.67241.76
48. Casa DJ, DeMartini JK, Bergeron MF, et al. National athletic trainers' association position statement: exertional heat illnesses. *J Athl Train*. 2015;50(9):986–1000. doi:10.4085/1062-6050-50.9.07
49. Cleary M. Predisposing risk factors on susceptibility to exertional heat illness: clinical decision-making considerations. *J Sport Rehabil*. 2007;16(3):204–214. doi:10.1123/jsr.16.3.204
50. Popowski LA, Oppliger RA, Lambert P, Johnson RF, Johnson AK, Gisolf CV. Blood and urinary measures of hydration status during progressive acute dehydration. *Med Sci Sports Exer*. 2001;33(5):747–753. doi:10.1097/00005768-200105000-00011
51. Armstrong LE. Rehydration during endurance exercise: challenges, research, options, methods. *Nutrients*. 2021;13(3):887. doi:10.3390/nu13030887
52. Armstrong LE, Johnson EC, Casa DJ, et al. The American football uniform: uncompensable heat stress and hyperthermic exhaustion. *J Athl Train*. 2010;45(2):117–127. doi:10.4085/1062-6050-45.2.117
53. Wilson PB. Nutrition behaviors, perceptions, and beliefs of recent marathon finishers. *Physician Sportsmed*. 2016;44(3):242–251. doi:10.1080/00913847.2016.1177477
54. Winger JM, Dugas JP, Dugas LR. Beliefs about hydration and physiology drive drinking behaviours in runners. *Br J Sports Med*. 2011;45(8):646–649. doi:10.1136/bjsm.2010.075275
55. Sekiguchi Y, Benjamin CL, Butler CR, et al. Relationships between WUT (body weight, urine color, and thirst level) criteria and urine indices of hydration status. *Sports Health*. 2022;14(4):566–574. doi:10.1177/19417381211038494
56. Casa DJ, Stearns RL, Lopez RM, et al. Influence of hydration on physiological function and performance during trail running in the heat. *J Athl Train*. 2010;45(2):147–156. doi:10.4085/1062-6050-45.2.147
57. Lopez RM, Casa DJ, Jensen KA, et al. Examining the influence of hydration status on physiological responses and running speed during trail running in the heat with controlled exercise intensity. *J Strength Cond Res*. 2011;25(11):2944–2954. doi:10.1519/JSC.0b013e318231a6c8
58. Armstrong LE, Casa DJ, Emmanuel H, et al. Nutritional, physiological, and perceptual responses during a summer ultraendurance cycling event. *J Strength Cond Res*. 2012;26(2):307–318. doi:10.1519/JSC.0b013e318240f677
59. Armstrong LE, Johnson EC, Kunces LJ, et al. Drinking to thirst versus drinking ad libitum during road cycling. *J Athl Train*. 2014;49(5):624–631. doi:10.4085/1062-6050-49.3.85
60. Armstrong LE, Johnson EC, McKenzie AL, Ellis LA, Williamson KH. Ultraendurance cycling in a hot environment: thirst, fluid consumption, and water balance. *J Strength Cond Res*. 2015;29(4):869–876. doi:10.1519/JSC.0000000000000822
61. Armstrong LE, Johnson EC, McKenzie AL, Ellis LA, Williamson KH. Endurance cyclist fluid intake, hydration status, thirst, and thermal sensations: gender differences. *Int J Sport Nutr Exerc Metab*. 2016;26(2):161–167. doi:10.1123/ijsnem.2015-0188
62. Lee MY, Khong TK, Ramliy N, Yusof A. Relationship between objective and subjective hydration measures on sprint performance among soccer players during actual matches in hot and humid environment. *J Sports Med Phys Fitness*. 2021;62(11):1560–1567. doi:10.23736/S0022-4707.21.13413-9
63. Engell DB, Maller O, Sawka MN, Francesconi RN, Drolet L, Young AJ. Thirst and fluid intake following graded hypohydration levels in humans. *Physiol Behav*. 1987;40(2):229–236. doi:10.1016/0031-9384(87)90212-5
64. Ceylan B, Aydos L, Simenko J. Effect of rapid weight loss on hydration status and performance in elite judo athletes. *Biology*. 2022;11(4):article500. doi:10.3390/biology11040500
65. Fernandez-Elias VE, Martinez-Abellan A, Lopez-Gullon JM, et al. Validity of hydration non-invasive indices during the weightcutting and official weigh-in for Olympic combat sports. *PLoS One*. 2014;9(4):articlee95336. doi:10.1371/journal.pone.0095336
66. Hew-Butler T, Rosner MH, Fowkes-Godek S, et al. Statement of the third international exercise-associated hyponatremia consensus development conference, Carlsbad, California, 2015. *Clin J Sport Med*. 2015;25(4):303–320. doi:10.1097/JSM.0000000000000221

67. Kratz A, Ferraro M, Sluss PM, Lewandrowski KB. Case records of the Massachusetts general hospital. Weekly clinicopathological exercises. laboratory reference values. *N Engl J Med*. 2004;351(15):1548–1563. doi:10.1056/NEJMcpc049016
68. Armstrong LE, Giersch GEW, Dunn L, Fiol A, Munoz CX, Lee EC. Inputs to thirst and drinking during water restriction and rehydration. *Nutrients*. 2020;12(9):article2554. doi:10.3390/nu12092554
69. Elliott KB, Keefe MS, Rolloque JS, et al. Relationships between morning thirst and later hydration status and total water intake. *Nutrients*. 2024;16(18):article3212. doi:10.3390/nu16183212
70. Keefe MS, Luk HY, Rolloque JS, Jiwan NC, McCollum TB, Sekiguchi Y. The weight, urine colour and thirst Venn diagram is an accurate tool compared with urinary and blood markers for hydration assessment at morning and afternoon timepoints in euhydrated and free-living individuals. *Br J Nutr*. 2024;131(7):1181–1188. doi:10.1017/S000711452300274X
71. Campbell P, Martin D, Bargh MJ, Gee TI. A comparison of rapid weight loss practices within international, national and regional powerlifters. *Nutr Health*. 2023;article2601060231201892. doi:10.1177/02601060231201892
72. Khodaee M, Olewinski L, Shadgan B, Kiningham RR. Rapid weight loss in sports with weight classes. *Curr Sports Med Rep*. 2015;14 (6):435–441. doi:10.1249/JSR.0000000000000206
73. Adams WM, Vandermark LW, Belval LN, Casa DJ. The utility of thirst as a measure of hydration status following exercise-induced dehydration. *Nutrients*. 2019;11(11):article2689. doi:10.3390/nu11112689
74. Maughan RJ, Shirreffs SM. Rehydration and recovery after exercise. *Sci Sports*. 2004;19(5):234–238. doi:10.1016/j.scispo.2004.05.003
75. Armstrong LE. Hydration assessment techniques. *Nutr Rev*. 2005;63(6):S40–S54. doi:10.1111/j.1753-4887.2005.tb00153.x
76. Munoz CX, Bergeron MF. Characterizing hydration practices in healthy young recreationally active adults-is there utility in first morning urine sampling? *Int J Sport Nutr Exerc Metab*. 2023;33(5):265–274. doi:10.1123/ijsnem.2022-0203
77. Perrier ET, Armstrong LE, Daudon M, et al. From state to process: defining hydration. *Obes Facts*. 2014;7(Suppl 2):6–12. doi:10.1159/000360611
78. Armstrong LE, Johnson EC, Munoz CX, et al. Hydration biomarkers and dietary fluid consumption of women. *J Acad Nutr Diet*. 2012;112 (7):1056–1061. doi:10.1016/j.jand.2012.03.036
79. Armstrong LE, Pumerantz AC, Fiala KA, et al. Human hydration indices: acute and longitudinal reference values. *Int J Sport Nutr Exerc Metab*. 2010;20(2):145–153. doi:10.1123/ijsnem.20.2.145
80. Cheuvront SN, Fraser CG, Kenefick RW, Ely BR, Sawka MN. Reference change values for monitoring dehydration. *Clin Chem Lab Med*. 2011;49(6):1033–1037. doi:10.1515/CCLM.2011.170
81. Racinais S, Alonso JM, Coutts AJ, et al. Consensus recommendations on training and competing in the heat. *Scand J Med Sci Sports*. 2015;25:6–19. doi:10.1111/sms.12467
82. Racinais S, Hosokawa Y, Akama T, et al. IOC consensus statement on recommendations and regulations for sport events in the heat. *Br J Sports Med*. 2023;57(1):8–25. doi:10.1136/bjsports-2022-105942
83. Volpe SL, Poule KA, Bland EG. Estimation of prepractice hydration status of national collegiate athletic association division I athletes. *J Athl Train*. 2009;44(6):624–629. doi:10.4085/1062-6050-44.6.624
84. Barley OR, Chapman DW, Abbiss CR. Reviewing the current methods of assessing hydration in athletes. *J Int Soc Sports Nutr*. 2020;17(1): article52. doi:10.1186/s12970-020-00381-6
85. Cheuvront SN, Carter R, Montain SJ, Sawka MN. Daily body mass variability and stability in active men undergoing exercise-heat stress. *Int J Sport Nutr Exerc Metab*. 2004;14(5):532–540. doi:10.1123/ijsnem.14.5.532
86. Cheuvront SN, Haymes EM, Sawka MN. Comparison of sweat loss estimates for women during prolonged high-intensity running. *Med Sci Sports Exer*. 2002;34(8):1344–1350. doi:10.1097/00005768-200208000-00017
87. Grandjean AC, Reimers KJ, Bannick KE, Haven MC. The effect of caffeinated, non-caffeinated, caloric and non-caloric beverages on hydration. *J Am Coll Nutr*. 2000;19(5):591–600. doi:10.1080/07315724.2000.10718956
88. Grandjean AC, Reimers KJ, Haven MC, Curtis GL. The effect on hydration of two diets, one with and one without plain water. *J Am Coll Nutr*. 2003;22(2):165–173. doi:10.1080/07315724.2003.10719290
89. Armstrong LE, Maresh CM, Castellani JW, et al. Urinary indices of hydration status. *Int J Sport Nutr Exerc Metab*. 1994;4(3):265–279. doi:10.1123/ijsn.4.3.265
90. Zubac D, Paravlic A, Reale R, Jelaska I, Morrison SA, Ivancev V. Fluid balance and hydration status in combat sport Olympic athletes: a systematic review with meta-analysis of controlled and uncontrolled studies. *Eur J Nutr*. 2019;58(2):497–514. doi:10.1007/s00394-019-01937-2
91. Johnson EC, Munoz CX, Le Bellego L, et al. Markers of the hydration process during fluid volume modification in women with habitual high or low daily fluid intakes. *Eur J Appl Physiol*. 2015;115(5):1067–1074. doi:10.1007/s00421-014-3088-2
92. Manz F, Wentz A. 24-h hydration status: parameters, epidemiology and recommendations. *Eur J Clin Nutr*. 2003;57(Suppl 2):S10–S18. doi:10.1038/sj.ejcn.1601896
93. Perrier ET, Bottin JH, Vecchio M, Lemetais G. Criterion values for urine-specific gravity and urine color representing adequate water intake in healthy adults. *Eur J Clin Nutr*. 2017;71(4):561–563. doi:10.1038/ejcn.2016.269
94. Adams JD, Myatich AI, McCullough AS. Thirst as an ingestive behavior: a brief review on physiology and assessment. *Nutr Health*. 2020;26 (3):271–274. doi:10.1177/0260106020916972
95. Perrier E, Demazieres A, Girard N, et al. Circadian variation and responsiveness of hydration biomarkers to changes in daily water intake. *Eur J Appl Physiol*. 2013;113(8):2143–2151. doi:10.1007/s00421-013-2649-0
96. Wardenaar FC. Human hydration indices: spot urine sample reference values for urine concentration markers in athletic populations. *Dietetics*. 2022;1(1):39–51. doi:10.3390/dietetics1010005
97. Armstrong LE, Herrera-Soto JA, Hacker FT, Casa DJ, Kavouras SA, Maresh CM. Urinary indices during dehydration, exercise, and rehydration. *Int J Sport Nutr Exerc Metab*. 1998;8(4):345–355. doi:10.1123/ijsn.8.4.345
98. Zubac D, Reale R, Karnincic H, Sivric A, Jelaska I. Urine specific gravity as an indicator of dehydration in Olympic combat sport athletes; considerations for research and practice. *Eur J Sport Sci*. 2018;18(7):920–929. doi:10.1080/17461391.2018.1468483
99. Adolph EF, Barker JP, Hoy PA. Multiple factors in thirst. *Am J Physiol*. 1954;178(3):538–562. doi:10.1152/ajplegacy.1954.178.3.538

100. Allen WE, Chen MZ, Pichamoorthy N, et al. Thirst regulates motivated behavior through modulation of brainwide neural population dynamics. *Science*. 2019;364(6437):article253. doi:10.1126/science.aav3932
101. Armstrong LE, Kavouras SA. Thirst and drinking paradigms: evolution from single factor effects to brainwide dynamic networks. *Nutrients*. 2019;11(12):article2864. doi:10.3390/nu11122864
102. Johnson AK. The sensory psychobiology of thirst and salt appetite. *Med Sci Sports Exer*. 2007;39(8):1388–1400. doi:10.1249/mss.0b013e3180686de8
103. Peck JW. Discussion: thirst resulting from bodily water imbalances. In: Epstein AN, Kissileff HR, Stellar E, editors. *The Neuropsychology of Thirst: New Findings and Advances in Concepts*. Washington, DC: VH Winston & Sons; 1973:99–112.
104. Saker P, Farrell MJ, Adib FR, Egan GF, McKinley MJ, Denton DA. Regional brain responses associated with drinking water during thirst and after its satiation. *Proc Natl Acad Sci U S A*. 2014;111(14):5379–5384. doi:10.1073/pnas.1403382111
105. Stevenson RJ, Mahmut M, Rooney K. Individual differences in the interoceptive states of hunger, fullness and thirst. *Appetite*. 2015;95:44–57. doi:10.1016/j.appet.2015.06.008
106. Stricker EM, Sved AF. Thirst. *Nutrition*. 2000;16(10):821–826. doi:10.1016/s0899-9007(00)00412-3
107. Akoglu H. User's guide to correlation coefficients. *Turk J Emerg Med*. 2018;18(3):91–93. doi:10.1016/j.tjem.2018.08.001
108. Bichet DG. Vasopressin and the Regulation of Thirst. *Ann Nutr Metab*. 2018;72(suppl 2):3–7. doi:10.1159/000488233
109. Bouby N, Clark WF, Roussel R, Taveau C, Wang CJ. Hydration and kidney health. *Obes Facts*. 2014;7(suppl 2):19–32. doi:10.1159/000360889
110. May M, Jordan J. The osmopressor response to water drinking. *Am J Physiol Regul Integr Comp Physiol*. 2011;300(1):R40–R46. doi:10.1152/ajpregu.00544.2010
111. Shore AC, Markandu ND, Sagnella GA, et al. Endocrine and renal response to water loading and water restriction in normal man. *Clin Sci*. 1988;75(2):171–177. doi:10.1042/cs0750171
112. Bankir L, Bichet DG, Morgenthaler NG. Vasopressin: physiology, assessment and osmosensation. *J Intern Med*. 2017;282(4):284–297. doi:10.1111/joim.12645
113. Bichet DG. Vasopressin at central levels and consequences of dehydration. *Ann Nutr Metab*. 2016;68(Suppl 2):19–23. doi:10.1159/000446200
114. Figaro MK, Mack GW. Regulation of fluid intake in dehydrated humans: role of oropharyngeal stimulation. *Am J Physiol*. 1997;272(6 Pt 2): R1740–R1746. doi:10.1152/ajpregu.1997.272.6.R1740
115. Armstrong LE, Johnson EC, Ganio MS, et al. Effective body water and body mass changes during summer ultra-endurance road cycling. *J Sports Sci*. 2015;33(2):125–135. doi:10.1080/02640414.2014.932918
116. Maughan RJ, Shirreffs SM, Leiper JB. Errors in the estimation of hydration status from changes in body mass. *J Sports Sci*. 2007;25 (7):797–804. doi:10.1080/02640410600875143
117. Chan YH. Biostatistics 104: correlational analysis. *Singapore Med J*. 2003;44(12):614–619.
118. Frizzell RT, Lang GH, Lowance DC, Lathan SR. Hyponatremia and ultramarathon running. *J Am Med Assoc*. 1986;255(6):772–774. doi:10.1001/jama.1986.03370060086025
119. Noakes TD, Goodwin N, Rayner BL, Branken T, Taylor RK. Water intoxication: a possible complication during endurance exercise. *Med Sci Sports Exer*. 1985;17(3):370–375. doi:10.1249/00005768-198506000-00012
120. Hiller WD. Dehydration and hyponatremia during triathlons. *Med Sci Sports Exer*. 1989;21(Suppl 5):S219–S221.
121. Hoffman MD, Hew-Butler T, Stuempfle KJ. Exercise-associated hyponatremia and hydration status in 161-km ultramarathoners. *Med Sci Sports Exer*. 2013;45(4):784–791. doi:10.1249/MSS.0b013e31827985a8
122. Hoffman MD, Stuempfle KJ. Sodium Supplementation and Exercise-Associated Hyponatremia during Prolonged Exercise. *Med Sci Sports Exer*. 2015;47(9):1781–1787. doi:10.1249/MSS.0000000000000599
123. Stover EA, Zachwieja J, Stofan J, Murray R, Horswill CA. Consistently high urine specific gravity in adolescent American football players and the impact of an acute drinking strategy. *Int J Sports Med*. 2006;27(4):330–335. doi:10.1055/s-2005-865667
124. Armstrong LE, Casa DJ. Methods to evaluate electrolyte and water turnover of athletes. *Athl Train Sports Health Care*. 2009;1(4):169–179. doi:10.3928/19425864-20090625-06
125. Maughan RJ, Shirreffs SM. Development of individual hydration strategies for athletes. *Int J Sport Nutr Exerc Metab*. 2008;18(5):457–472. doi:10.1123/ijsnem.18.5.457
126. Bennett BL, Hew-Butler T, Rosner MH, Myers T, Lipman GS. Wilderness medical society clinical practice guidelines for the management of exercise-associated hyponatremia: 2019 update. *Wilderness Environ Med*. 2020;31(1):50–62. doi:10.1016/j.wem.2019.11.003
127. Ganio MS, Armstrong LE, Kavouras SA. Hydration. In: Casa DJ, editor. *Sport and Physical Activity in the Heat: Maximizing Performance and Safety*. Cham, CH: Springer; 2018:83–100.
128. Knechtle B, Knechtle P, Wirth A, Rüst CA, Rosemann T. A faster running speed is associated with a greater body weight loss in 100-km ultra-marathoners. *J Sports Sci*. 2012;30(11):1131–1140. doi:10.1080/02640414.2012.692479
129. Rüst CA, Knechtle B, Knechtle P, Wirth A, Rosemann T. Body mass change and ultraendurance performance: a decrease in body mass is associated with an increased running speed in male 100-km ultramarathoners. *J Strength Cond Res*. 2012;26(6):1505–1516. doi:10.1519/JSC.0b013e318231a7b5
130. Cheuvront SN, Ely BR, Kenefick RW, Sawka MN. Biological variation and diagnostic accuracy of dehydration assessment markers. *Am J Clin Nutr*. 2010;92(3):565–573. doi:10.3945/ajcn.2010.29490
131. O'Neal EK, Johnson SL, Davis BA, Pribyslavska V, Stevenson-Wilcoxson MC. Urine specific gravity as a practical marker for identifying suboptimal fluid intake of runners ~ 12-hr postexercise. *Int J Sport Nutr Exerc Metab*. 2019;29(1):32–38. doi:10.1123/ijsnem.2017-0383
132. Wilcoxson MCS, Johnson SL, Pribyslavska V, Green JM, O'Neal EK. Fluid retention and utility of practical hydration markers to detect three levels of recovery fluid intake in male runners. *Int J Sport Nutr Exerc Metab*. 2017;27(2):178–185. doi:10.1123/ijsnem.2015-0362
133. Minton DM, EK O, Torres-McGehee TM. Agreement of urine specific gravity measurements between manual and digital refractometers. *J Athl Train*. 2015;50(1):59–64. doi:10.4085/1062-6050-49.3.47
134. Lee EC, Fragala MS, Kavouras SA, Queen RM, Pryor JL, Casa DJ. Biomarkers in sports and exercise: tracking health, performance, and recovery in athletes. *J Strength Cond Res*. 2017;31(10):2920–2937. doi:10.1519/JSC.0000000000002122
135. Buell JL, Franks R, Ransone J, et al. National athletic trainers' association position statement: evaluation of dietary supplements for performance nutrition. *J Athl Train*. 2013;48(1):124–136. doi:10.4085/1062-6050-48.1.16

136. Hespel P, Maughan RJ, Greenhaff PL. Dietary supplements for football. *J Sports Sci*. 2006;24(7):749–761. doi:10.1080/02640410500482974
137. Maughan RJ, Burke LM, Dvorak J, et al. IOC consensus statement: dietary supplements and the high-performance athlete. *Br J Sports Med*. 2018;52(7):439–455. doi:10.1136/bjsports-2018-099027
138. Rodriguez NR, Di Marco NM, Langley S. American college of sports medicine position stand. Nutrition and athletic performance. *Med Sci Sports Exer*. 2009;41(3):709–731. doi:10.1249/MSS.0b013e31890eb86
139. Ellis LA, Yates BA, McKenzie AL, Munoz CX, Casa DJ, Armstrong LE. Effects of three oral nutritional supplements on human hydration indices. *Int J Sport Nutr Exerc Metab*. 2016;26(4):356–362. doi:10.1123/ijsnem.2015-0244
140. Yates BA, Ellis LA, Munoz CX, Armstrong LE. Diagnostic accuracy of urinary indices to detect mild dehydration in young men following acute riboflavin, Vitamin C or beetroot supplementation. *Clin Nutr ESPEN*. 2020;37:129–133. doi:10.1016/j.clnesp.2020.03.006
141. Perucca J, Bouby N, Valeix P, Bankir L. Sex difference in urine concentration across differing ages, sodium intake, and level of kidney disease. *Am J Physiol Regul Integr Comp Physiol*. 2007;292(2):R700–R705. doi:10.1152/ajpregu.00500.2006
142. Wilson PB. Associations of urine specific gravity with body mass index and lean body mass at the population level: implications for hydration monitoring. *Int J Sport Nutr Exerc Metab*. 2021;31(6):475–481. doi:10.1123/ijsnem.2021-0140
143. Armstrong LE, Ganio MS, Klau JF, Johnson EC, Casa DJ, Maresh CM. Novel hydration assessment techniques employing thirst and a water intake challenge in healthy men. *Appl Physiol Nutr Metab*. 2014;39(2):138–144. doi:10.1139/apnm-2012-0369
144. McDermott BP, Casa DJ, Yeargin SW, Ganio MS, Lopez RM, Mooradian EA. Hydration status, sweat rates, and rehydration education of youth football campers. *J Sport Rehab*. 2009;18(4):535–552.
145. Yeargin SW, Casa DJ, Judelson DA, et al. Thermoregulatory responses and hydration practices in heat-acclimatized adolescents during preseason high school football. *J Athl Train*. 2010;45(2):136–146. doi:10.4085/1062-6050-45.2.136
146. Funnell MP, Juett LA, Ferrara R, Mears SA, James LJ. Ad-libitum fluid intake was insufficient to achieve euhydration 20 h after intermittent running in male team sports athletes. *Physiol Behav*. 2023;268:article114227. doi:10.1016/j.physbeh.2023.114227
147. Cheuvront SN, Haymes EM. Ad libitum fluid intakes and thermoregulatory responses of female distance runners in three environments. *J Sports Sci*. 2001;19(11):845–854. doi:10.1080/026404101753113796
148. Cheuvront SN, Haymes EM. Thermoregulation and marathon running: biological and environmental influences. *Sports Med*. 2001;31:743–762. doi:10.2165/00007256-200131100-00004
149. Noakes TD. Fluid replacement during exercise. *Exerc Sport Sci Rev*. 1993;21(1):297–330. doi:10.1249/00003677-199301000-00010
150. McKenzie AL, Munoz CX, Armstrong LE. Accuracy of urine color to detect equal to or greater than 2% body mass loss in men. *J Athl Train*. 2015;50(12):1943–1949. doi:10.4085/1062-6050-51.1.03
151. Perrier ET, Johnson EC, McKenzie AL, Ellis LA, Armstrong LE. Urine colour change as an indicator of change in daily water intake: a quantitative analysis. *Eur J Nutr*. 2016;55:1943–1949. doi:10.1007/s00394-015-1010-2
152. Hew-Butler T, Verbalis JG, Noakes TD. Updated fluid recommendation: position statement from the international marathon medical directors association (IMMDA). *Clin J Sport Med*. 2006;16(4):283–292. doi:10.1097/00042752-200607000-00001
153. Connor J, Egan B. Prevalence, magnitude and methods of rapid weight loss reported by male mixed martial arts athletes in Ireland. *Sports*. 2019;7(9):article206. doi:10.3390/sports7090206
154. Kons RL, Da Silva Athayde MS, Follmer B, Detanico D. Methods and magnitudes of rapid weight loss in judo athletes over pre-competition periods. *Hum Mov*. 2017;18(2):49–55. doi:10.1515/humo-2017-0014
155. Langan-Evans C, Close GL, Morton JP. Making weight in combat sports. *Strength Conditioning J*. 2011;33(6):25–29. doi:10.1519/SSC.0b013e318231bb64
156. Martinez-Rodriguez A, Vicente-Salar N, Montero-Carretero C, Cervello-Gimeno E, Roche E. Weight loss strategies in male competitors of combat sport disciplines. *Medicina*. 2021;57(9):article897. doi:10.3390/medicina57090897
157. Matthews JJ, Stanhope EN, Godwin MS, Holmes MEJ, Artioli GG. The magnitude of rapid weight loss and rapid weight gain in combat sport athletes preparing for competition: a systematic review. *Int J Sport Nutr Exerc Metab*. 2019;29(4):441–452. doi:10.1123/ijsnem.2018-0165
158. Reale R, Slater G, Cox GR, Dunican IC, Burke LM. The effect of water loading on acute weight loss following fluid restriction in combat sports athletes. *Int J Sport Nutr Exerc Metab*. 2018;28(6):565–573. doi:10.1123/ijsnem.2017-0183
159. Burke LM, Slater GJ, Matthews JJ, Langan-Evans C, Horswill CA. ACSM expert consensus statement on weight loss in weight-category sports. *Curr Sports Med Rep*. 2021;20(4):199–217. doi:10.1249/JSR.0000000000000831
160. Kirk C, Langan-Evans C, Morton JP. Worth the weight? Post weigh-in rapid weight gain is not related to winning or losing in professional mixed martial arts. *Int J Sport Nutr Exerc Metab*. 2020;30(5):357–361. doi:10.1123/ijsnem.2019-0347
161. Reale R, Slater G, Burke LM. Weight management practices of Australian Olympic combat sport athletes. *Int J Sports Physiol Perform*. 2018;13(4):459–466. doi:10.1123/ijspp.2016-0553
162. Melander O. Vasopressin, from regulator to disease predictor for diabetes and cardiometabolic risk. *Ann Nutr Metab*. 2016;68(Suppl 2):24–28. doi:10.1159/000446201
163. Muñoz CX, Johnson EC, McKenzie AL, et al. Habitual total water intake and dimensions of mood in healthy young women. *Appetite*. 2015;92:81–86. doi:10.1016/j.appet.2015.05.002
164. Perrier E, Vergne S, Klein A, et al. Hydration biomarkers in free-living adults with different levels of habitual fluid consumption. *Br J Nutr*. 2013;109(9):1678–1687. doi:10.1017/S0007114512003601
165. Agostoni CV, Bresson JL, Fairweather-Tait S, et al. Scientific opinion on dietary reference values for water. *EFSA J*. 2010;8(3):article1459. doi:10.2903/j.efsa.2010.1459
166. Institute of Medicine. *Dietary. Reference Intakes for Water, Potassium, Sodium, Chloride, and Sulfate*. Washington, DC: The National Academies Press; 2005. doi:10.17226/10925
167. Armstrong LE, Bergeron MF, Muñoz CX, Kavouras SA. Low daily water intake profile—is it a contributor to disease? *Nutr Health*. 2024;30(3): article02601060241238826. doi:10.1177/02601060241238826