Hydration in Sport and Exercise

6

Louise M. Burke

6.1 Introduction

During most types of exercise, the evaporation of sweat plays a substantial role in the dissipation of excess heat produced by the working muscle or absorbed from the environment (see Chap. 2). Although this activity is a foundation of the thermoregulatory response to exercise, its side-effect is to reduce body water stores. Athletes and other people who exercise can counter sweat losses by consuming fluid during the session or, in a lesser contribution, by hyperhydrating prior to the exercise bout. However, in the majority of situations, the opportunity or desire to drink cannot keep pace with sweat losses, leading to a body fluid deficit. Furthermore, some athletes may commence the session with pre-existing hypohydration, due to the failure to replace daily environmental sweat losses and/or reverse the fluid deficit from a prior exercise bout. The goal of this chapter is to summarise the current status of our knowledge around hydration and exercise, with a focus on practical strategies to assess and address fluid deficits associated with *exercise*. Consideration of hydration and *sport* requires additional context, since it must address the real-world significance of the effects of hypohydration on performance as well as the effect of the rules and logistics of organised events/activities on the practicality of fluid intake.

L. M. Burke (✉)
Australian Institute of Sport, Belconnen, ACT, Australia

Mary MacKillop Institute for Health Research, Australian Catholic University, Melbourne, VIC, Australia
e-mail: Louise.burke@ausport.gov.au

J. D. Périard, S. Racinais (eds.), *Heat Stress in Sport and Exercise*,
https://doi.org/10.1007/978-3-319-93515-7_6

6.2 Terminology and Physiology of Hypohydration/Dehydration

In brief, the fluid content of the human body (total body water; TBW) typically fluctuates by ~1% of body mass (BM) each day, according to changes in the intake of water (food and fluids), metabolic water production and fluid loss (sweat, urine, faeces and respiratory fluid losses) [1, 2]. Figure 6.1 summarises the components involved in daily fluid balance in a sedentary individual, noting that the higher water losses of athletes can create a large imbalance unless water intake from fluids and foods is increased appropriately. Although exercise changes TBW balance by increasing metabolic water production and insensible losses via respiration, its principle effect is to increase total sweat loss. The reduction of body fluids by 2% BM (~3% TBW) from levels of euhydration, to clear the threshold of daily biological variation [2], is termed "hypohydration", and although the strict definition of "dehydration" is the process of reaching a fluid deficit, these terms are often used interchangeably.

Consumption of fluid to (temporarily) increase TBW above the normal daily variation is termed hyperhydration. In the context of exercise, this strategy may be deliberately undertaken by athletes prior to events in which a large fluid deficit is expected to occur due to the inability to drink sufficient volumes of fluid in relation to large sweat losses. Here, the athlete may drink large amounts of fluids in the hours prior to the event, often in conjunction with an osmotically active agent such as glycerol or sodium, with the goal of producing a temporary increase in total body water to offset sweat losses and delay the progression of absolute hypohydration from becoming physiologically significant [3]. However, it may also occur

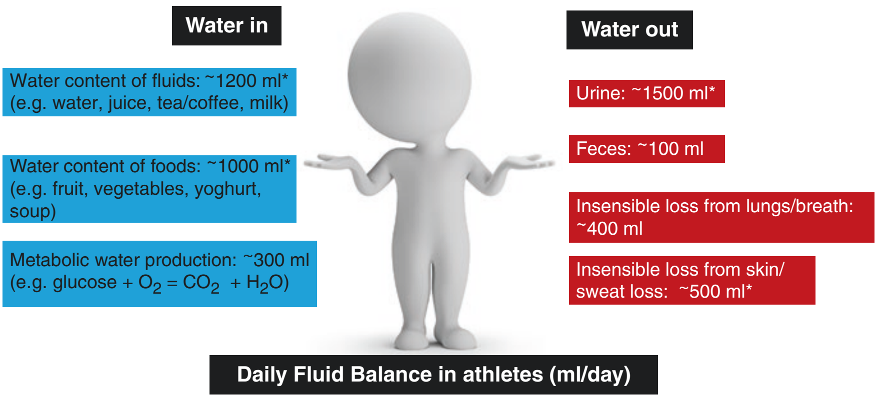


Fig. 6.1 Daily water balance in an athlete. Figures are approximate and represent baseline values for a sedentary person. * An athlete's sweat losses are likely to be substantially increased and must be balanced by greater intake of fluids, as well as greater intake of water from foods

unintentionally during exercise if an athlete consumes fluid in excess of their actual sweat losses: this practice has been identified as an outcome of flawed fluid intake guidelines for sport (or, flawed understanding of these guidelines) and when carried out to extremes may lead to the serious consequences associated with water intoxication/hyponatremia [4].

6.2.1 Sweat Losses in Exercise and Sport

Sweat rates during exercise vary markedly according to the type and intensity of the activity, the environmental conditions in which it occurs (temperature, humidity, wind speed, altitude, etc.), the size and body composition of the athlete, their clothing or other protective gear and their degree of training status and acclimatisation [5–7]. Prediction equations have been established to estimate sweat losses associated with many of these variables [6]. Although these estimates are valuable in providing general advice around education guidelines or fluid provision to populations who exercise purposefully or within their daily occupation (e.g. the military or manual labourers) [6], it is acknowledged that they are generally unable to account for the complexity of the interaction of these factors in real life [7]. Measurements of sweat losses associated with various types of exercise and sporting pursuits show that the typical sweat rates of athletes can vary from 300 to 2000 L/h [8, 9]. Tables 6.1 and 6.2 summarise some of the published observations of fluid balance during competitive sports events, noting sweat rates, typical fluid intakes and the degree of BM loss (i.e. proxy for fluid mismatch) encountered during a variety of different types of activities.

6.2.2 Brief Summary of the Physiological Effects of Hypohydration

Dehydration causes loss of intracellular and extracellular (plasma and interstitial) fluid in proportion to the loss of water and solutes. Typically, sweat is hypotonic (i.e. lower in electrolyte concentration) with respect to plasma; therefore, exercise-associated sweat losses lead to a reduction in plasma volume and increase in its electrolyte concentration (principally, sodium) known as hypertonic hypovolemia. Meanwhile, hypohydration due to the use of some diuretics, or the diuresis associated with altitude and cold environments, produces an isotonic hypovolemia (for review, see [5]). The physiological effects of hypohydration on exercise have been best characterised during aerobic/submaximal exercise, particularly when performed in the heat. It is noted that exercise in the heat creates a "relative hypohydration" of its own, due to the redistribution of blood flow to the skin to assist with heat dissipation [40, 41]. In combination, there is a significant increase in cardiovascular strain, with an elevation in heart rate to accommodate the reduction in stroke

Table 6.1 Fluid balance characteristics of sporting competitions of continuous duration

Study	Subjects	Event	Duration (min)	Environment (°C, %)	Sweat rate (L/h)	Δ Body mass (%)	Fluid intake (L/h)
Single-day endurance and ultra-endurance events							
Beis et al. [10]	10 M Elite (race winners)	13 different Olympic/Big City Marathons	126 ± 1	Air: 0–30 Humidity: 39–89	NR	N/A	0.55 ± 0.34
Mettler et al. [11]	128 M, 39 F Mixed-calibre athletes	Zurich Marathon	220 ± 32 (M) 245 ± 23 (F)	Air: ~10 Humidity: raining	NR	−0.8 ± 0.8 (M) −0.2 ± 0.8 (F)	0.47 (M) 0.36 (F)
Hew [12]	63 M, 54 F Mixed-calibre athletes	Houston Marathon	269 ± 45 (M) 303 ± 54 (F)	NR	NR	−2.1 (M) [−1.7 ± 1.8 kg] −1.0 (F) [−0.6 ± 1.1 kg]	0.74 (M) 0.68 (F)
Pahnke et al. [13]	26 M, 20 F Mixed-calibre athletes	Hawaii Ironman triathlon	NR	Air: 27.6 Humidity: NR	NR	−2.1 ± 2.1	0.85 ± 0.30 (M) 1.05 ± 0.30 (F)
Speedy et al. [14]	292 M, 38 F Mixed-calibre athletes	New Zealand Ironman triathlon	734	Air: 21, Water: 20.7 Humidity: 91	NR	−4.3 ± 2.3 (M) −2.7 ± 3.1 (F)	NR
Speedy et al. [15]	46 M + 2 F Mixed-calibre athletes	Coast to Coast New Zealand (paddle/ride/run)	879 ± 83	Air: 7.5–19.6 Humidity: 56–94	NR	−3.1 ± 2.1	NR
Kao et al. [16]	19 M, 4 F Mixed-calibre athletes	Soochow University International 24-h running event	1440 (199.4 ± 37 km)	Air: 11.5–14.6 Humidity: 55–60	NR	−5.1 ± 2.3	NR
Glace et al. [17]	13 M + F Mixed-calibre athletes	160-km trail run Start time 0430	1572 ± 216	Air: 21–38 Humidity: NR	NR	−0.5 (−0.5 ± 1.5 kg)	0.74
Fallon et al. [18]	7 M Mixed-calibre athletes	100-km road run	629 ± 113	Air: 2–17 Humidity: 45	0.86 ± 0.15	−3.3 ± 1.1	0.54 ± 0.21

Armstrong et al. [19]	42 M, 6 F Mixed-calibre athletes	164-km cycle event, USA	546 ± 72 (M) 540 ± 12 (F)	Air: 34.5 ± 5.0 Humidity: 53	1.13	N/A	0.65 (M) 0.52 (F)
Knechtle et al. [20]	37 M Mixed-calibre athletes	Swiss MTB Bike Masters 120 km	540 ± 80	Air: 11 (at start) Humidity: NR	NR	−1.9 ± 1.6	0.7 ± 0.2
Brearley et al. [21]	4 M Professional drivers	V8 Supercar Championship Race	31 ± 7	Air: 29, Cabin: 49 Humidity: NR	1.06 ± 0.12	−0.6 ± 0.6	NR
Multi-day Stage race (cycling or running)							
Ross et al. [22]	5 M Elite cycling team	Tour of Gippsland (NRS stage race) 9 stages over 5 days		Air: 15.8 ± 1.4 Humidity: 54 ± 12	1.1 ± 0.3	− 1.5 ± 0.3 (road race) − 1.1 ± 0.2 (criterium)	0.41 ± 0.19 (road race) 0.24 ± 0.19 (criterium)
Ebert et al. [23]	8 M Elite Professional team	Tour down under 719 km in 6 days	NR	Air: 20.2–32.9 Humidity: 14–69	1.60 ± 0.10	−2.8	1.00 ± 0.10
Ebert et al. [23]	6 F Elite cycling team	Tour De L'Aude 788 km in 10 days	NR	Air: 7.7–27.8 Humidity: 29–76	0.90	−2.6	0.40 ± 0.06
Garcia-Roves et al. [24]	10 M Elite Professional team	3 × 24-h periods during the 3-week Tour of Spain	NR	NR	NR	NR	1.26 ± 0.55 L
Knechtle et al. [25]	25 M Mixed-calibre athletes	Swiss Jura Marathon 350 km in 7 stages	373 ± 50	NR	NR	−1.4 ± 2.0	0.54–0.75 (range)

Data are mean ± SD or [range] or not reported (NR) for male (M) and female (F) athletes

Table 6.2 Fluid balance characteristics of sporting events of intermittent nature or conducted in water environment

Study	Subjects	Event	Duration (min)	Environment (°C, %)	Sweat rate (L/h)	Δ Body mass (%)	Fluid intake (L/h)
Field sports: football and cricket							
Da Silva et al. [26]	10 M Elite youth players	Soccer match—Brazil	110	Air: 31.2 ± 2.0 Humidity: 48	~1.22	– 1.6 ± 0.8	~0.61
Aragon-Vargus et al. [27]	17 M Elite professional players	Soccer Match—Costa Rice Premier division	180	Air: 34.9 ± 1.2 Humidity: 35	1.48 ± 0.36	−3.4 ± 1.1	0.65
Maughan et al. [28]	20 M Elite professional players	Soccer Match—English Premier League	96	Air 6–8 Humidity: 50–60	1.09 (Team A) 1.01 (Team B)	– 0.9 ± 0.7 (Team A) – 1.3 ± 0.6 (Team B)	0.68 (Team A) 0.43 (Team B)
O'Hara et al. [29]	14 M Elite professional players	UK Super League Rugby League match	NR	Air :12.1 ± 5.3 Humidity: 70	NR	−1.2 ± 0.6 (Team A) −1.4 ± 0.7 (Team B)	1.12 L (Team A) 1.56 L (Team B)
Meir et al. [30]	28 M Elite development squad	<21 Rugby Union Championship (4 games; G1-4)	NR	Air: 18.5 ± 1.6 Humidity: 40	0.54 ± 0.55 (G1) 0.49 ± 0.65 (G2) 0.89 ± 0.65 (G3) 0.92 ± 0.88 (G4)	−0.8 ± 0.8 (G1) −0.7 ± 0.9 (G2) −1.3 ± 0.9 (G3) −1.3 ± 1.2 (G4)	NR
Gore et al. [31]	3 M First-grade bowlers	Cricket match	360[c]	Air: 32.8 ± 0.5 Humidity: 29	1.37 ± 0.06	−4.3 ± 0.7	0.46
Court sports—tennis, basketball and ice hockey							
Osterberg et al. [32]	29 M Professional basketball players	NBA Match	40 (playing time = 21 ± 8)	Air: 20–22 °C Humidity: 18–22	3.30	−1.4 ± 0.6	1.50

Tippet et al. [33]	7 F Professional tennis players	WTA match Hard court	119.9 ± 40.1	Air: 30.3 ± 2.3 Humidity: NR	2.00 ± 0.50	−1.2 ± 1.0	1.5 ± 0.50
Bergeron et al. [34]	12 M, 8 F Sub-elite players	US Division 1 Collegiate tournament: Hard court	90	Air: 32.2 ± 1.5 Humidity: 54 ± 2	1.8 (M) 1.1 (F)	−1.3 ± 0.8 (M) −0.7 ± 0.8 (F)	1.13 (M) 0.87 (F)
Logan-Sprenger et al. [35]	24 M Elite junior ice hockey players	Ontario Hockey League	210[c]	Air: 10.8 ± 0.2 Humidity: 30 ± 2	0.90	−1.3 ± 0.3	0.68
Water-based sports							
Cox et al. [36]	23 M Elite Australian squad	Tournament	47	Air: 24.1 Water: 27.3 Humidity: 54	0.79	−0.4	0.38
Wagner et al. [37]	25 M, 11 F Mixed-calibre athletes	26.4-km swim Switzerland	528 (M) 599 (F)	Air: 18.5–28.1 Water: 22.9–24.1 Humidity: 42–93	NR	− 0.5 ± 1.1 (M) − 0.1 ± 1.6 (F)	0.56 ± 0.22 (M) 0.44 ± 0.17 (F)
Neville et al. [38]	32 M Professional crew	Lead up race to America's Cup	150	Air: 32 ± 1 Humidity: 52 ± 5	0.96 ± 0.38	−0.7 ± 0.8	0.64
Slater et al. [39]	26 M, 9 F Club level dinghy crew	Club regatta Singapore	300	Air: 29–33 Humidity: 62–81	0.47 (M) 0.23 (F)	−2.1 (M) −0.9 (F)	0.24 (M) 0.16 (F)

Data are mean ± SD or [range] or not reported (NR) for male (M) and female (F) athletes volume [42]. Competition between peripheral and central circulation for the reduced plasma volume can lead to a decrease in muscle blood flow and aerobic reserve, and particularly as plasma osmolality increases, a reduced sweat rate for any given core temperature and an increase in heat storage (for review, see [40, 41, 43]). Increased rates of muscle glycogen usage, motor unit recruitment and afferent feedback, as well as elevations in skin temperature, discomfort and thirst-derived distraction are among the many factors associated with hypohydration, particularly when exercise is undertaken in a warm-hot environment [40, 41, 43]. Studies that have monitored the effect of hypohydration on physiological responses to exercise in the heat have noted that the magnitude of impairment is linearly related to the magnitude of the fluid deficit [42]. For a more detailed account of the effects of hypohydration on physiological characteristics during exercise, the reader is referred to recent comprehensive reviews [8, 40, 41, 43].

6.3 Assessment of Hydration Status

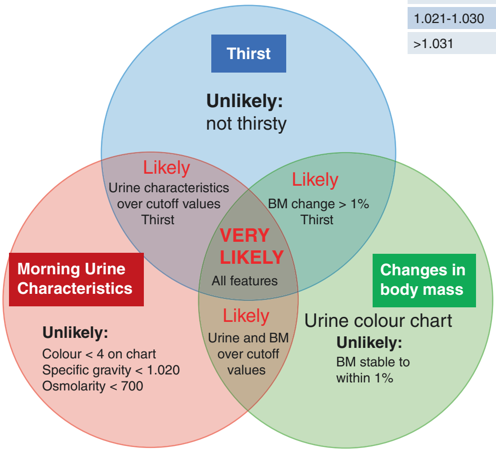
In the laboratory, various techniques such as the use of tracer-labelled water, bioelectrical impedance and blood characteristics allow the tracking of TBW. In the real world of both research and athletic practice, however, there is a need for techniques that are less expensive, invasive or resource/time heavy to gain information about an individual's current hydration status as well as to monitor the fluid deficit that might occur during exercise and require replacement. The accuracy of any assessment technique involves the concept of sensitivity (identifying correctly when a state is present) and specificity (recording a negative outcome when the state is absent).

6.3.1 Assessing Current Hydration Status

In research, clinical practice or athlete servicing, there are various situations in which it is desirable to know an individual's current hydration status. The requirement here is to identify changes in body fluid status that are greater than biological variability. The gold standard for measurement of TBW involves the isotope dilution method (usually deuterium oxide) which can measure changes in TBW of ~1% [44]. However, this is an expensive method requiring analytical resources and expertise; furthermore, it requires a baseline measurement in the individual to monitor change rather than to identify an absolute cut-off deemed to represent hypohydration. The measurement of plasma osmolality, which is controlled around a euhydration set-point of ~285 mOsm/kg, can also be used as a marker of hydration status, with a change of ~5 mOsm/kg equating to a fluid loss of ~2% BM [45]. However, this is an invasive technique, which again requires expense and laboratory resources, and may not always reflect changes in TBW in some scenarios faced by athletes (e.g. altitude). Bioelectrical impedance analysis (BIA) is a non-invasive technique that can be used to estimate TBW, on the basis that the resistance to low amperage current (single or multiple frequencies) passed between skin electrodes varies inversely with tissue water and electrolyte content. Although it may provide a reliable measure of TBW in euhydrated individuals, it lacks sensitivity in measuring loss of TBW and shifts between body fluid compartments [46].

The simplest and most practical measurements of hydration status, particularly for field work, involve measurements of urine characteristics and alterations in BM. In the absence of energy deficits/surpluses and changes in diet that alter the mass of gut contents, acute monitoring of morning BM (after voiding) provides a simple measurement of success in maintaining TBW [47]. Changes in urinary concentration can be readily assessed via comparison to colour charts (Fig. 6.2) or by the use of portable refractometers and osmometers to measure specific gravity and osmolality, respectively [48]. Spot checks of urine characteristics over the day are liable to false negatives for various reasons. For example, if a dehydrated individual rapidly rehydrates or consumes large amounts of fluid without replacement of the solutes lost in sweat, diuresis of pale and dilute urine will occur until there is full replacement of electrolytes, with sufficient time for requilibration of plasma osmolality and volume, and distribution of fluid across the various compartments [49]. Therefore, it is recommended that first void morning urine samples be used for assessment of hydration status [1, 48], particularly for serial assessments in the same individual over time, where an individual "normal" can be established. Investigation of the utility of monitoring other body fluids such as saliva or tears has so far failed to produce alternatives that are accurate and free of artefacts [1, 2].

Urine Specific Gravity	Urine osmolality (mOsm/kg)	Interpretation
1.001-1.010	>350	Well hydrated/hyper-hydrated
1.011-1.020	350-700	Euhydrated
1.021-1.030	700-1050	Hypohydrated
>1.031	>1050	Severely hypohydrated



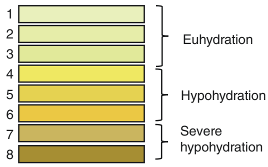


Fig. 6.2 An assessment of fluid balance can be made by examining thirst, characteristics of the first voided morning urine sample and changes in morning body mass (BM). If two or more of the characteristics fall outside the levels associated with euhydration, there is a likely risk of hypohydration. Adapted from [50, 51]. Note that cut-offs in the reference ranges for euhydration and hypohydration may differ slightly between different expert groups

Finally, given the opportunity for each assessment technique to be confounded by artefacts or lack of precision around the individual demarcation of euhydration vs hypohydration, it has been suggested that athletes develop their personal metrics around cut-offs or use a combination of techniques to provide a more robust diagnosis (see Fig. 6.2). Note that these strategies may affirm the presence of hypohydration, but can provide only a qualitative assessment of the magnitude of the fluid deficit (e.g. what might be considered moderate/tolerable vs severe/problematic by the individual athlete or specific scenario) rather than precise determination (e.g. the fluid deficit is *x* mL). Indeed, although there have been many attempts to provide specific metrics to describe these situations (e.g. a fluid deficit equivalent to 2–3% BM might be considered "mild", while severe equates to a fluid deficit of >5% BM), the context around these values requires greater consideration and interpretation. Further information on methods of hydration assessment can be found in recent publications [1, 2, 51].

6.3.2 Assessing Fluid Balance Across an Exercise Session

Athletes often want to assess fluid balance across an exercise session to gauge their typical sweat rates, the success of their usual fluid intake practices in addressing these and/or the residual fluid deficit that needs to be replaced during the recovery period. Typically, this is undertaken by monitoring changes in BM, adjusted for intake over the session, in the belief that, during short-medium duration exercise (2–3 h) at least, BM changes mirror changes in TBW. In such circumstances, calculations of sweat and TBW loss summarised in Table 6.3 can provide a reasonable assessment of relative fluid changes during the workout or event, since both the contribution of substrate depletion to BM changes and the provision of TBW from metabolic water production or liberation of water from glycogen are minor in comparison with sweat losses. It is noted that interpretations of fluid status from this information requires an acknowledgement of the athlete's pre-existing hydration level (i.e. whether the apparent fluid change over the session needs to be adjusted for pre-exercise hyperhydration tactics or a carryover of a fluid deficit from previous exercise or weight-making strategies), as well as errors involved in weighing the trapped fluid in clothes and hair during pre- or post-exercise weigh in [52]. Studies show that the adjustment of calculations for urine losses, trapped sweat and intake during the exercise session can improve calculations of sweat losses [53]. In the case of very prolonged exercise sessions (>3–4 h) where metabolic water production and liberation of water from glycogen become significant, and measurable amounts of body carbohydrate and fat stores contribute to substrate use, there is a need to adjust sweat rate and TBW calculations. For example, modelling of fluid characteristics of an ultra-endurance run lasting 24–30 h suggested that ~2–5% BM needed to be subtracted from BM changes to assess true change in TBW [54]. Despite the challenges, assessing fluid balance over typical exercise sessions with careful strategies and insights can help athletes to develop or monitor drinking practices that neither over- or under-hydrate inappropriately.

Table 6.3 Strategies to estimate fluid balance across a session of exercise

Steps	1. Weigh athlete's body mass (BM) before session, using reliable digital scales (ideally measuring to 0.01 kg). This should be done wearing minimal clothing and after the athlete has gone to the toilet 2. Weigh athlete again after session in the same clothing, and after towelling dry 3. Weigh athlete's drink bottle before and after the session (ideally measuring to 1 g using kitchen scales) to calculate the volume (g/mL) of fluid consumed 4. Note the mass (g) of any foods or sports products (e.g. gels) consumed during the session
Extra steps for further accuracy	5. If the athlete has to go to the toilet during the session, weigh in before and after, or collect urine in a beaker to measure the volume/mass 6. Estimate total urine losses during the session by having athlete weigh in post-session, go to the toilet, and reweigh (alternatively, collect urine in beaker and measure the volume). Add this to the volume/mass of urine produced at any mid-session toilet stops
Calculations	*Fluid intake (mL)* = drink bottle before − drink bottle after (g) *705 g − 104 g* = 601 *g or 601 mL* *Urine losses (mL)* = change in BM due to toilet stops during and/or after the session: kg × 1000 or g *e.g. weight change: 60.25 − 60.00 = 0.25 kg = 250 mL or 251 g urine in beaker* *Fluid deficit (mL)* = Pre-session BM − Post-session BM (kg) × 1000. (Note: to measure total fluid deficit which includes sweat and urine losses, use post-session value taken after the toilet visit) *60.50 − 59.05 = 1.45 kg = 1450 mL* *Fluid deficit (% BM)* = (Fluid deficit [in kg] × 100)/pre-session BM (kg) *(1.45 × 100)/(60.50) = 2.4%* *Total sweat losses over the session* = Fluid deficit (g) + fluid intake (g) + food intake (g) − urine losses (g) *1450 + 601 + 40 g (sports gel) − 250 = 1841 mL* *Sweat rate over the session* = sweat losses converted to mL per h *Session lasted for 90 min: sweat rate = 1841 × 60/90 = 1227 mL or 1.23 L/h*
Interpretation issues	While this activity can provide an estimate of the net fluid deficit incurred across a session of exercise, some issues should be considered • Pre-session hydration status needs to be taken into account to distinguish between relative and absolute fluid deficits. If the athlete has pre-existing hypohydration, the total fluid deficit is underestimated by these calculations. By contrast, if the athlete has hyper-hydrated prior to the session, the net fluid deficit will be overestimated • During prolonged exercise (>2–3 h) at high workloads, the contribution of other factors to TBW changes may no longer be insignificant. For example: failure to adjust for BM loss from depletion of fuels (e.g. glycogen), liberation of water from glycogen breakdown and metabolic water production may contribute to an overestimation of the true fluid loss. For ultra-endurance events of 4–24 h, estimates of the true fluid deficit might require an adjustment of 2–5% BM • Sources of error due to fluids trapped in clothes and hair should also be considered

6.4 Effect of Dehydration on Performance

Despite more than five decades of research, the impact of hypohydration on the performance of exercise, or more specifically, sport, is a contentious topic [55, 56]. Although the effects of hypohydration on physiological parameters are well established, there are a number of factors related both to the published literature on hydration and performance and observations of real-life outcomes of sporting events that create debate about the real impact of hypohydration on sports performance. Clearly, the translation of physiological and psychological effects of hypohydration into changes in sports performance will be mediated by characteristics such as the individual athlete, the type of event, the environmental conditions in which it is conducted, the importance of absolute vs relative performance (i.e. does the athlete need to perform optimally or just better than other competitors?) and whether the event was commenced with pre-existing hypohydration or whether it accumulated over the session. Several reviews have identified flaws in the conduct of laboratory-based studies of hydration and performance, including their lack of integration of the environmental conditions, motivational incentives and success determinants of real-life sport as well as their failure to capture the timing and magnitude of hypohydration to which athletes are commonly exposed [56, 57]. Some of the issues underpinning the debate around the application of the literature on hypohydration to sporting success are identified in Fig. 6.3. These include factors that support the hypothesis that performance is impaired by hypohydration, as well as factors that suggest that the effects of hypohydration are overstated.

Table 6.4 summarises the conclusions from a number of review papers which have conducted narrative and systematic reviews, including some meta-analyses, of the studies of hypohydration and exercise/sports performance. The summation of this literature shows some discrepancies, but also the likelihood that hypohydration impairs performance to a degree that is meaningful to competitive success in certain scenarios. This risk is greatest for aerobic exercise undertaken in hot conditions and when skin temperature is raised, when the fluid deficit exceeds 3% BM and perhaps, when there is an overlay of skill and cognitive performance [59–63]. Of course, it should be noted that amalgamation of data may mask the frailties of individual studies, particularly those conducted without insight into the specific conditions of real-life sport, and that athletes should be more interested in understanding the risks associated with their individual scenarios rather than seeking a universal truth. Data on fluid balance characteristics measured across a range of competitive sporting events (Tables 6.1 and 6.2) show that both groups and individual athletes commonly achieve a BM deficit of >2% within their activities, and although measurements of elite competitors are relatively scarce, it is likely that they are at greater risk of exposure to levels of hypohydration that have been associated with a performance decrement.

There is a need for new research on hypohydration and sports performance with protocols that reflect the conditions under which hypohydration occurs and measure the impact on performance in ways that are meaningful to competition outcomes.

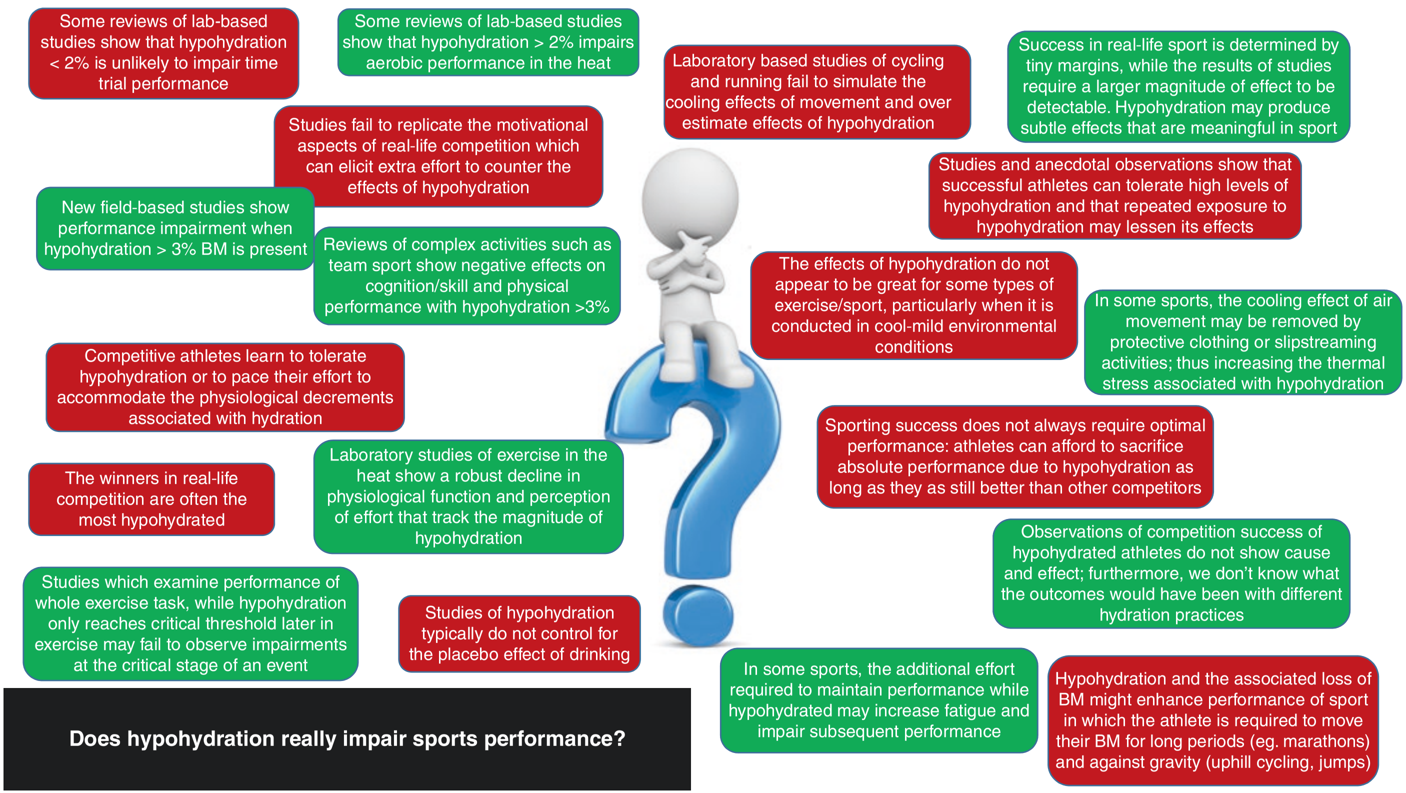


Fig. 6.3 Considerations underpinning the debate over the effect of hypohydration on sports performance; red boxes denote concepts that downplay the effect, while green boxes denote concepts that support the negative effect of hypohydration on performance. Adapted from [58]

One theme of interest is the removal of an important confounder of the hydration literature: removal of the placebo effect of fluid intake during exercise and/or the blinding of study participants to alterations in their hydration status during performance trials. This challenge was tackled in a study of recreational athletes who cycled in hot conditions [64], by utilising a protocol involving oral intake of small amounts of fluid to provide identical sensory exposure in each trial while manipulating hydration via the infusion of different volumes of fluid intake into the stomach with a nasogastric tube. The hypohydration trial in this investigation achieved a mean BM loss of 2.4% at the end of 155 min of intermittent cycling (8 × 15 min + 5 min rest) compared with 0.1% in the euhydration trial. This protocol achieved an increase in heart rate, perceived effort and thirst, and a hypertonic

Table 6.4 Reviews of hypohydration and exercise/sports performance from the recent decade

Review	Topic	Method	Key conclusions
Nuccio et al. [59]	Effect of hypohydration on cognitive, technical and physical performance in team sports	Systematic narrative review of lab/field studies of high-intensity intermittent exercise involving team athletes as participants, examining effects of hypohydration on cognitive performance and technical skill (n = 17) and/or physical performance (sprinting, jumping, etc.) [n = 15] with defined criteria for acceptance into analysis	• The effect of hypohydration on team sport performance is mixed • Hypohydration is more likely to impair cognition, technical skill and physical performance at higher levels of BM loss (>3% BM), especially when heat stress is involved • Increased ratings of perceived effort and fatigue consistently accompany hypohydration and could explain some of the performance impairment
Savoie et al. [60]	Effect of hypohydration on muscle endurance, strength, anaerobic power and capacity, and vertical jumping ability	Systematic review and meta-analysis of lab studies (n = 28) of controlled and single efforts involving muscle strength (upper body = 14 effects, and lower body = 25 effects), endurance (n = 6 and 10), anaerobic power and capacity (n = 9), and vertical jumping ability (n = 12) with defined criteria for acceptance into analysis	• Hypohydration significantly impairs muscular endurance in both upper and lower body by ~8% • Hypohydration significantly impairs muscular strength by ~5% with similar effects on upper and lower body • Anaerobic power is significantly reduced (~6%) by hypohydration but effects on anaerobic capacity (-3%) and vertical jump (+1%) are not significant • Trained individuals demonstrate a 3% lower decrease in effects on performance than untrained subjects

Table 6.4 (continued)

Review	Topic	Method	Key conclusions
Cheuvront and Kenefick [61]	Effect of hypohydration on endurance and strength/ power exercise	Narrative review of lab/field studies of hypohydration on endurance (n = 34 with 60 effects) and strength (n = 43 studies with 267 effects) with defined criteria for acceptance into analysis Review counted how many effects recorded an impairment of performance/ exercise capacity with different levels of hypohydration (see Fig. 6.4)	• Among studies of endurance exercise, 41/60 (68%) effects were significantly impaired by hypohydration of ≥2% BM, rising to 53/60 (88%) if absolute impairment (including non-significant changes) was considered • The effects are increased in hot environments, and when skin temperature is increased • Among studies of strength/ power exercise, 54/276 (20%) reported significant impairment of effects, showing that the effect of hypohydration on strength or power are marginal • Effects on cognition appear to be small and related to distraction or discomfort • The effect of hypohydration on a particular sport related to the makeup of the task involved
Goulet [62]	Effect of hypohydration on endurance performance	Systematic review and meta-analysis of lab studies (n = 15, with 28 effects) with defined criteria for acceptance into analysis	• Hypohydration of >2% BM did not alter time trial performance (mean change of +0.1%); it is unlikely that hypohydration <4% BM impairs performance under real-world conditions • Hypohydration of >2% significantly impaired performance of fixed intensity protocols by 1.9%; hypohydration is associated with an impairment of endurance capacity
Judelson et al. [63]	Effect of hypohydration on strength, power and high-intensity exercise	Narrative review of lab studies of hypohydration on muscle power, strength and high-intensity exercise (>2 min and <10 min) noting those with exacerbating and masking factors, and emphasising 11 studies determined as being accurate in isolating effect of hypohydration on exercise	• Hypohydration appears to consistently attenuate strength by ~2%, power by ~3% and high-intensity endurance by ~10%

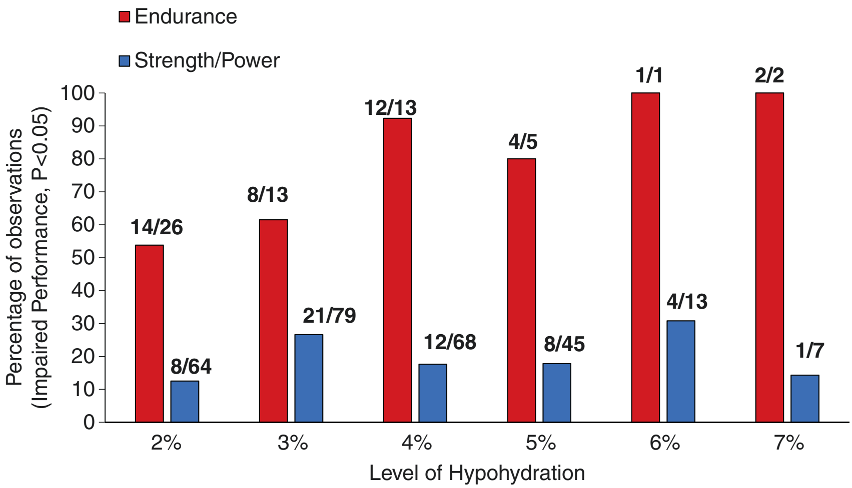


Fig. 6.4 Summary of a narrative review of studies of the effect of hypohydration on endurance (34 studies) and strength/power performance (43 studies) [61]. The studies are arranged according to the level of hypohydration achieved in the study, noting the percentage of the studies which found a significant impairment of performance. Redrawn with permission

hypovolemia in the hypohydration trial, as would be expected from a real-life trial. Performance (work achieved during a 15-min time trial at the end of this pre-load) was reduced by 8% in the hypohydration trial. The authors acknowledge that two previous studies [65, 66], using similar protocols around gastric infusion of fluids to blind hydration status, recorded contradictory outcomes, failing to detect an impairment of performance in the hypohydration trials. However, the protocols used in these studies (no oral intake and delivery of isotonic fluid to the gut) failed to mimic the differential physiological and perceptual effects consistent with real-life hypohydration and adequate fluid intake.

A further investigation from a different laboratory implemented the same protocol in a more highly trained population, who cycled for 2 h before undertaking a 5-km time trial on a 4% grade on a laboratory ergometer in hot conditions [67]. Conditions just before the start of the time trial were a mean BM loss of −0.2 and −2.2% in the euhydrated and hypohydrated trials, respectively. Heart rates were elevated during the steady state pre-load with the hypohydrated condition but were identical during the time trial ride although performance was improved in the euhydration trial (32.9 s faster, 6% increase in power output). Rectal temperatures were elevated during the hypohydration time trial above the control condition, although thirst sensation was identical between trials suggesting that impairment of performance via hypohydration can occur independently of thirst. Further research of this type which eliminates the effects of expectation on performance outcomes associated with hypohydration, and differentiates thirst perception from physiological effects such as thermoregulatory and cardiac strain is encouraged.

6.5 Guidelines for Fluid Intake During Sport and Exercise

The past five decades have also seen a marked evolution of guidelines for fluid intake during sport and exercise and the range of issues address within them. Several critical events and position stands are described in brief summary. The first guidelines were issued in the 1970s and were directed to distance running events, addressing both the restrictions on fluid intake within official race rules (fluid intake was restricted prior to 15 km and then 11 km in road races, under the direction of the International Amateur Athletic Federation) as well as the culture of runners to consider fluid intake during marathons and ultra-marathons to be detrimental and a sign of weakness/lack of fitness [68]. These guidelines, within a larger paper on prevention of heat injuries during distance running, recommended that water or dilute glucose/electrolyte solutions be provided regularly in events longer than 16 km [69]. The 1996 publication of specific guidelines for fluid intake during exercise by the American College of Sports Medicine (ACSM) also largely focused on running and promoted pro-active and formulaic intake of fluid with the goal of minimising the mismatch between fluid intake and sweat losses [70].

During the following decade, there was increased recognition of the syndrome of hyponatremia/water intoxication caused by the excessive intake of fluids by some (usually recreational) participants in endurance/ultra-endurance sports activities resulting in a small but concerning number of cases of morbidity and mortality from cerebral oedema [15, 71, 72]. Hyponatremia, which is diagnosed by measurement of plasma sodium concentrations, ranges from a mild drop below the normal range (e.g. <135 mmol/L) which may be largely asymptomatic to the severe drop (<120 mmol/L) which is associated with major problems [4]. The 2007 update of the ACSM guidelines [8] was undertaken to address this issue and reduce any misunderstanding that its previous iteration encouraged athletes/recreational exercisers to "drink as much as possible" during exercise. The revised position promoted the development of individualised fluid intake plans ("programmed drinking") across a range of sporting activities, with the goal of defending (where possible) a "gold standard" of hydration (suggested as loss of <2% BM over the event) but warning against over-drinking (shown by a gain in BM) [8].

Despite this clarification, the ACSM position stand has attracted harsh criticism and counterarguments that humans need only drink fluids "to thirst" or "ad libitum" during exercise/sporting activities. Furthermore, it has been postulated that opinions to the contrary represent flawed research supported by biased sports scientists and commercial interest in the sale of sports drinks [73–75]. Other more recent expert statements on fluid intake during exercise, underpinned by an interest in preventing hyponatremia rather than focusing on performance effects and the cardiovascular/thermoregulatory stress associated with hypohydration, have championed this latter approach of "drinking to thirst" [4]. Curiously, case histories of hyponatremia have included athletes who claimed to be following thirst-driven drinking practices [4] and scenarios involving sodium depletion in concert with hypohydration [76], showcasing the complexity of fluid and electrolyte balance during prolonged exercise. Unfortunately, the current situation in relation to exercise fluid guidelines presents a challenge to contemporary sports scientists and athletes to choose between two camps promoting apparently opposite approaches ("programmed drinking" vs "drinking to thirst"/ad libitum drinking).

This author and others [77] propose that there is a middle ground for fluid guidelines for sport and exercise, noting that both viewpoints support the benefits of drinking during exercise and warn against drinking in excess of sweat losses or the TBW deficit. However, the route to achieving this is multi-factorial because of the differences in the conditions and context of an exercise session. These differences include the priorities of the exerciser (performance vs health/safety), and whether the conditions under which they exercise make it easy or difficult to drink in relation to their sweat rates. Just as there are a variety of influences on sweat rates and losses during exercise, there are a range of issues that influence fluid intake; these include access to fluid, ability to drink, gastrointestinal comfort, thirst, and cultural and personal beliefs [58]. Furthermore, fluid may be consumed not only to meet needs for water replacement but as a vehicle for intake of other performance-enhancing nutrients (carbohydrate and caffeine), to contribute to thermoregulation via the ingestion of cold or icy drinks or to promote a sensation of well-being via the oro-pharyngeal sensing of fluid [58]. Some of these issues are unique to the event and within the control of the athlete/exercising person, while others are beyond their control. This is especially the case for competitive sports where fluid intake can be determined by event rules, logistics or the need to balance the time spent consuming fluids within a race with the performance benefits [58]. Indeed, in many competitive sports, it is impossible for athletes to drink to thirst or to drink ad libitum, since opportunities to drink sufficient volumes of fluid do not align with the accrual of a fluid deficit or development of thirst. For example, the rules of soccer (football) prevent the intake of fluid during match play (45 min halves plus overtime). Meanwhile, practical restrictions around the volume of fluid can be obtained, consumed and tolerated at any single aid station by an elite marathon runner make it unlikely that thirst could be sufficiently subdued if allowed to fully develop.

Although drinking during exercise is considered an innate behaviour, controlled by biological cues and fine-tuned by evolution [78], Tables 6.1 and 6.2 illustrate that the patterns and drivers of fluid intake by athletes during competitive sporting events are extremely complex. These data and those from more comprehensive reviews [9, 59] report that across a range of sports, non-elite athletes typically appear to consume fluids at rates of 300–1000 mL/h, limiting the mean change in BM across the session to ~2%. From the sparse information on elite competitors, however, it seems likely that their fluid intakes during events are less able to keep pace with their greater sweat rates. Indeed, weight losses of ≥5% BM have been observed in some individuals, particularly during events undertaken in hot and/or humid conditions [10]. By contrast, some athletes (especially non-elite competitors) may have drinking behaviours that result in an undesirable gain in body mass over an event, with a small proportion of these progressing to symptomatic hyponatremia [4]. This apparent range in practices and outcomes confirms the multi-factorial nature of drinking behaviours.

Figure 6.5 identifies a range of factors that can exist within sport or exercise that can promote under-drinking or over-hydration, even within the same event or

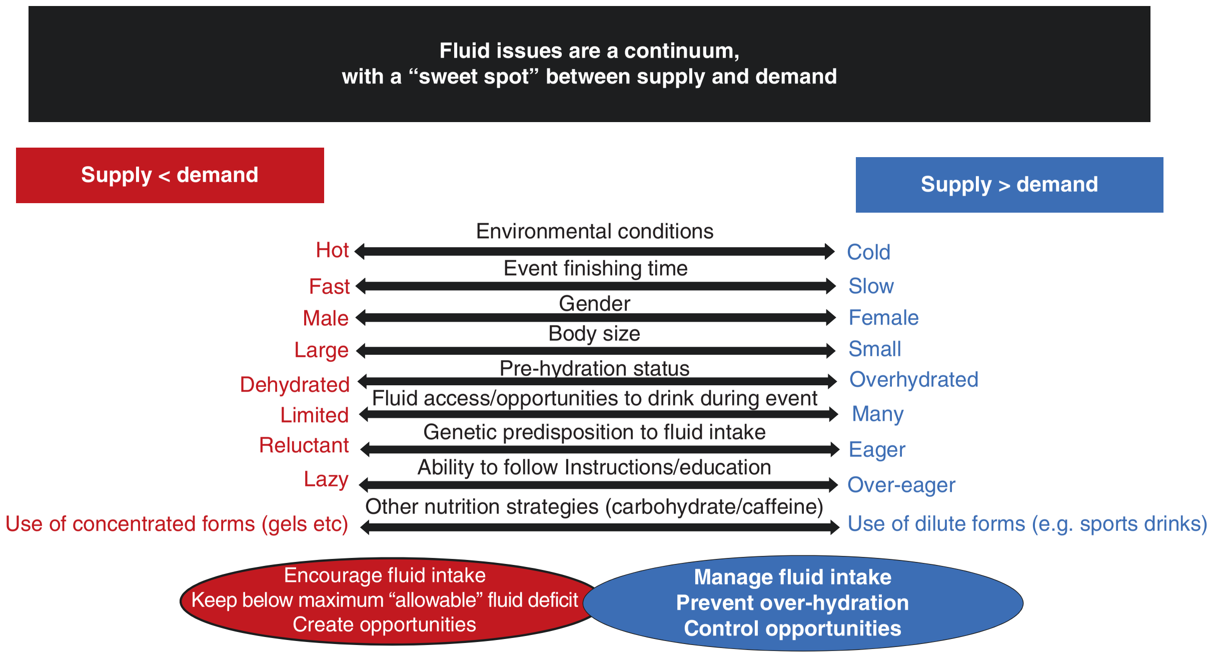


Fig. 6.5 A paradigm to illustrate that guidelines and practices around fluid intake in sport need to recognise that scenarios exist in which athletes may either overdrink or underdrink in comparison to their fluid losses, and that different strategies are needed to address these

individual. This suggests that guidance can be provided to athletes based on the likelihood that their sweat rates will be greatly higher than their opportunities/desire to drink, or the reverse. When factors align in the latter direction (e.g. it is cool, exercise is of moderate intensity and there are plenty of opportunities to consume fluids), it may be sufficient to drink to thirst, although some over-eager drinkers may also benefit from programmed drinking that limits total fluid intake. In contrast, when factors align to make likely sweat losses well in excess of fluid intake (e.g. hot weather, higher intensity exercise, few opportunities to access fluid and difficulty drinking large volumes on a single occasion), athletes can be guided to exploit the available opportunities with a fluid intake plan that limits the accrual of the TBW deficit.

In finishing this discussion, it is worth noting that over the last decade, as the debate between "drinking to thirst" and "programmed drinking" has developed, several studies have attempted to investigate the benefits of the "drinking to thirst" model, or in some cases, to discredit the benefit of a planned approach to hydration for athletic performance [79–82]. As in the general literature on hydration and sports performance, there are methodological issues arising from different practices being used to achieve "drinking to thirst/ad libitum" fluid intake as well as different practices of "programmed drinking"(ranging from complete replacement of BM losses to allowance of an accrual of 2% BM loss). It is interesting that the majority of studies have not found any differences in performance following these different approaches to managing hydration during running and cycling protocols [79–82]; this suggests that a range of practices can be tolerated or are associated with successful outcomes. Furthermore, a study involving 30 km of ergometer cycling in the heat [83] reported that programmed fluid intake which preserved BM to a mean loss <0.5% was associated with a faster performance in the last of three 5-km cycling time trials, than ad libitum drinking (mean BM loss of 1.8%). Clearly, more research is needed, but the available studies support a common sense and flexible attitude to the range of drinking practices that might be suitable for different athletes or exercise scenarios.

6.6 Conclusion

Hydration status adds an overlay to the physiological and perceptual responses to exercise, especially when it is carried out in the heat. Sweat losses vary according to features of the exercise activity, the environment and the athlete, while self-chosen fluid intakes are influenced by a similarly large range of factors. This is especially true during sporting competitions which contribute an additional layer of rules, logistical concerns and performance trade-offs. The real-life picture of hydration practices during exercise/sport is a complicated mix, where some athletes/events experience a large (>5% BM) loss of TBW, while others maintain TBW within a range that is likely well tolerated in terms of physiological strain and performance (<2% BM loss), some drink in excess leading to a gain in TBW and/or BM and a few develop problematic symptoms of hyponatremia/water intoxication. The difficulty of detecting small but meaningful performance effects associated with hypohydration as well as absolute and relative changes in hydration status adds further complexity to the topic. Therefore, it is unlikely that a simple and single guideline for fluid intake during sport and exercise activities will suit all needs and all scenarios. Further research on hypohydration, fluid intake and sports performance is needed, especially involving field scenarios or lab protocols that can better mimic real-life conditions and measure meaningful changes in physiology and performance. Both "ad libitum drinking" or "drinking to thirst" and "programmed fluid intake" protocols have a role in guiding hydration practices for exercise and sport; the best approach will vary according to the factors that influence the relative magnitude of sweat rates and opportunities to drink. Finding some unifying themes to guide education messages around fluid intake to athletes and other people who exercise will help to solve the current debates and confusion.

References

1. Cheuvront SN, Ely BR, Kenefick RW, Sawka MN. Biological variation and diagnostic accuracy of dehydration assessment markers. Am J Clin Nutr. 2010;92(3):565–73.
2. Cheuvront SN, Kenefick RW. Dehydration: physiology, assessment, and performance effects. Comp Physiol. 2014;4(1):257–85.
3. van Rosendal SP, Coombes JS. Glycerol use in hyperhydration and rehydration: scientific update. Med Sport Sci. 2012;59:104–12.
4. Hew-Butler T, Rosner MH, Fowkes-Godek S, Dugas JP, Hoffman MD, Lewis DP, et al. Statement of the 3rd international exercise-associated hyponatremia consensus development conference, Carlsbad, California, 2015. Br J Sports Med. 2015;49(22):1432–46.
5. Sawka MN, Cheuvront SN, Kenefick RW. Hypohydration and human performance: impact of environment and physiological mechanisms. Sports Med. 2015;45(Suppl 1):S51–60.
6. Gonzalez RR, Cheuvront SN, Montain SJ, Goodman DA, Blanchard LA, Berglund LG, et al. Expanded prediction equations of human sweat loss and water needs. J Appl Physiol. 2009;107(2):379–88.
7. Jay O, Webb P. Improving the prediction of sweat losses during exercise. J Appl Physiol. 2009;107(2):375–6.
8. American College of Sports Medicine, Sawka MN, Burke LM, Eichner ER, Maughan RJ, Montain SJ, et al. American College of Sports Medicine position stand. Exercise and fluid replacement. Med Sci Sports Exerc. 2007;39(2):377–90.
9. Garth A, Burke L. What do athletes drink during competitive sporting activities? Sports Med. 2013;43(7):539–64.
10. Beis LY, Wright-Whyte M, Fudge B, Noakes T, Pitsiladis YP. Drinking behaviors of elite male runners during marathon competition. Clin J Sport Med. 2012;22:254–61.
11. Mettler S, Rusch C, Frey WO, Bestmann L, Wenk C, Colombani PC. Hyponatremia among runners in the Zurich Marathon. Clin J Sport Med. 2008;18:344–9.
12. Hew TD. Women hydrate more than men during a marathon race. Hyponatremia in the houston marathon: a report on 60 cases. Clin J Sport Med. 2005;15:148–53.
13. Pahnke MD, Trinity JD, Zachwieja JJ, Stofan JR, Hiller WD, Coyle EE. Serum sodium concentration changes are related to fluid balance and sweat sodium loss. Med Sci Sports Exerc. 2010;42:1669–74.
14. Speedy DB, Noakes TD, Rogers IR, Thompson JM, Campbell RG, Kuttner JA, et al. Hyponatremia in ultradistance triathletes. Med Sci Sports Exerc. 1999;31:809–15.

15. Speedy DB, Campbell R, Mulligan G, Robinson DJ, Walker C, Gallagher P, et al. Weight changes and serum sodium concentrations after an ultradistance multisport triathlon. Clin J Sport Med. 1997;7:100–3.
16. Kao WF, Shyu CL, Yang XW, Hsu TF, Chen JJ, Kao WC, et al. Athletic performance and serial weight changes during 12- and 24-hour ultra-marathons. Clin J Sport Med. 2008;18:155–8.
17. Glace BW, Murphy CA, McHugh MP. Food intake and electrolyte status of ultramarathoners competing in extreme heat. J Am Coll Nutr. 2002;21:553–9.
18. Fallon KE, Broad E, Thompson MW, Reull PA. Nutritional and fluid intake in a 100-km ultramarathon. Int J Sport Nutr. 1998;8:24–35.
19. Armstrong LE, Casa DJ, Emmanuel H, Ganio MS, Klau JF, Lee EC, et al. Nutritional, physiological, and perceptual responses during a summer ultraendurance cycling event. J Strength Cond Res. 2012;26:307–18.
20. Knechtle B, Knechtle P, Rosemann T, Senn O. No dehydration in mountain bike ultramarathoners. Clin J Sport Med. 2009;19:415–20.
21. Brearley MB, Finn JP. Responses of motor-sport athletes to V8 supercar racing in hot conditions. Int J Sports Physiol Perform. 2007;2:182–91.
22. Ross ML, Stephens B, Abbiss CR, Martin DT, Laursen PB, Burke LM. Fluid balance, carbohydrate ingestion, and body temperature during men's stage-race cycling in temperate environmental conditions. Int J Sports Physiol Perform. 2014;9(3):575–82.
23. Ebert TR, Martin DT, Stephens B, McDonald W, Withers RT. Fluid and food intake during professional men's and women's road-cycling tours. Int J Sports Physiol Perform. 2007;2:58–71.
24. Garcia-Roves PM, Terrados N, Fernandez SF, Patterson AM. Macronutrients intake of top level cyclists during continuous competition—change in the feeding pattern. Int J Sports Med. 1998;19:61–7.
25. Knechtle B, Gnadinger M, Knechtle P, Imoberdorf R, Kohler G, Ballmer P, et al. Prevalence of exercise-associated hyponatremia in male ultraendurance athletes. Clin J Sport Med. 2011;21:226–32.
26. Da Silva RP, Mundel T, Natali AJ, Bara Filho MG, Alfenas RC, Lima JR, et al. Pre-game hydration status, sweat loss, and fluid intake in elite Brazilian young male soccer players during competition. J Sports Sci. 2012;30:37–42.
27. Aragon-Vargas LF, Moncada-Jimenez J, Hernandez-Elizondo J, Barrenechea A, Monge-Alvarado M. Evaluation of pre-game hydration status, heat stress, and fluid balance during professional soccer competition in the heat. Eur J Sport Sci. 2009;9:269–76.
28. Maughan RJ, Watson P, Evans GH, Broad N, Shirreffs SM. Water balance and salt losses in competitive football. Int. J. Sport Nutr Exerc Metab. 2007;17:583–94.
29. O'Hara JP, Jones BL, Tsakirides C, Carroll S, Cooke CB, King RF. Hydration status of rugby league players during home match play throughout the 2008 Super League season. Appl Physiol Nutr Metab. 2010;35:790–6.
30. Meir RA, Halliday AJ. Pre- and post-game body mass changes during an international rugby tournament. A Practical Perspective. J Strength Cond Res. 2005;19:713–6.
31. Gore CJ, Bourdon PC, Woolford SM, Pederson DG. Involuntary dehydration during cricket. Int J Sports Med. 1993;14:387–95.
32. Osterberg KL, Horswill CA, Baker LB. Pregame urine specific gravity and fluid intake by National Basketball Association players during competition. J Ath Train. 2009;44:53–7.
33. Tippet ML, Stofan JR, Lacambra M, Horswill CA. Core temperature and sweat responses in professional women's tennis players during tournament play in the heat. J Ath Train. 2011;46:55–60.
34. Bergeron MF, Maresh CM, Armstrong LE, Signorile JF, Castellani JW, Kenefick RW, et al. Fluid-electrolyte balance associated with tennis match play in a hot environment. Int J Sport Nutr. 1995;5:180–93.
35. Logan-Sprenger HM, Palmer MS, Spriet LL. Estimated fluid and sodium balance and drink preferences in elite male junior players during an ice hockey game. Appl Physiol Nutr Metab. 2011;36:145–52.

36. Cox GR, Broad EM, Riley MD, Burke LM. Body mass changes and voluntary fluid intakes of elite level water polo players and swimmers. J Sci Med Sport. 2002;5:183–93.
37. Wagner S, Knechtle B, Knechtle P, Rüst CA, Rosemann T. Higher prevalence of exercise-associated hyponatremia in female than in male open-water ultra-endurance swimmers: the 'Marathon-Swim' in Lake Zurich. Eur J Appl Physiol. 2012;112:1095–106.
38. Neville V, Gant N, Folland JP. Thermoregulatory demands of elite professional America's Cup yacht racing. Scand J Med Sci Sports. 2010;20:475–84.
39. Slater G, Tan B. Body mass changes and nutrient intake of dinghy sailors while racing. J Sports Sci. 2007;25:1129–35.
40. Sawka MN, Leon LR, Montain SJ, Sonna LA. Integrated physiological mechanisms of exercise performance, adaptation, and maladaptation to heat stress. Compr Physiol. 2011;1(4):1883–928.
41. Cheuvront SN, Kenefick RW, Montain SJ, Sawka MN. Mechanisms of aerobic performance impairment with heat stress and dehydration. J Appl Physiol. 2010;109(6):1989–95.
42. Montain SJ, Coyle EF. Influence of graded dehydration on hyperthermia and cardiovascular drift during exercise. J Appl Physiol. 1992;73(4):1340–50.
43. Sawka MN, Cheuvront SN, Kenefick RW. High skin temperature and hypohydration impair aerobic performance. Exp Physiol. 2012;97(3):327–32.
44. Ritz P. Methods of assessing body water and body composition. In: Arnaud MJ, editor. Hydration throughout life. Vittel: Perrier Vittel Water Institute; 1998. p. 63–74.
45. Popowski LA, Oppliger RA, Patrick Lambert G, Johnson RF, Kim Johnson A, Gisolf CV. Blood and urinary measures of hydration status during progressive acute dehydration. Med Sci Sports Exerc. 2001;33(5):747–53.
46. O'Brien C, Young AJ, Sawka MN. Bioelectrical impedance to estimate changes in hydration status. Int J Sports Med. 2002;23:361–6.
47. 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;14:532–40.
48. Armstrong LE, Maresh CM, Castellani JW, Bergeron MF, Kenefick RW, LaGasse KE, et al. Urinary indices of hydration status. Int J Sport Nutr. 1994;4:265–79.
49. Kovacs EM, Senden JM, Brouns F. Urine color, osmolality and specific electrical conductance are not accurate measures of hydration status during postexercise rehydration. J Sports Med Phys Fitness. 1999;39(1):47–53.
50. Cheuvron SN, Sawka MN. SSE#97: hydration assessment of athletes. Gatorade Sports Sci Exchange 2005;18(2).
51. Armstrong LE, Pumerantz AC, Fiala KA, Roti MW, Kavouras SA, Casa DJ, et al. Human hydration indices: acute and longitudinal reference values. Int J Sport Nutr Exerc Metab. 2010;20(2):145–53.
52. Baker LB, Reimel AJ, Sopeña BC, Barnes KA, Nuccio RP, De Chavez PJD, Stofan JR, et al. Trapped sweat in basketball uniforms and the effect on sweat loss estimates. Physiol Rep. 2017 5(18). pii: e13463. https://doi.org/10.14814/phy2.13463.
53. Cheuvront SN, Haymes EM, Sawka MN. Comparison of sweat loss estimates for women during prolonged high-intensity running. Med Sci Sports Exerc. 2002;34(8):1344–50.
54. Hoffman MD, Goulet EDB, Maughan RJ. Considerations in the use of body mass change to estimate change in hydration status during a 161-kilometer ultramarathon running competition. Sports Med. 2018;48(2):243–50.
55. Sawka MN, Noakes TD. Does dehydration impair exercise performance? Med Sci Sports Exerc. 2007;39(8):1209–17.
56. Cotter JD, Thornton SN, Lee JK, Laursen PB. Are we being drowned in hydration advice? Thirsty for more? Extrem Physiol Med. 2014;3:18.
57. Maughan RJ. Investigating the associations between hydration and exercise performance: methodology and limitations. Nutr Rev. 2012;70(Suppl 2):S128–31.
58. Burke LM, Patterson AM, Cox GR, Armstrong LE. Concepts in developing better guidelines for fluid intake during sporting events: is drinking to thirst the answer? In review.

59. Nuccio RP, Barnes KA, Carter JM, Baker LB. Fluid balance in team sport athletes and the effect of hypohydration on cognitive, technical, and physical performance. Sports Med. 2017;47(10):1951–82.
60. Savoie FA, Kenefick RW, Ely BR, Cheuvront SN, Goulet ED. Effect of hypohydration on muscle endurance, strength, anaerobic power and capacity and vertical jumping ability: a meta-analysis. Sports Med. 2015;45(8):1207–27.
61. Cheuvront SN, Kenefick RW. Dehydration: physiology, assessment, and performance effects. Compr Physiol. 2014;4(1):257–85.
62. Goulet ED. Effect of exercise-induced dehydration on endurance performance: evaluating the impact of exercise protocols on outcomes using a meta-analytic procedure. Br J Sports Med. 2013;47(11):679–86.
63. Judelson DA, Maresh CM, Anderson JM, Armstrong LE, Casa DJ, Kraemer WJ, et al. Hydration and muscular performance: does fluid balance affect strength, power and high-intensity endurance? Sports Med. 2007;37(10):907–21.
64. James LJ, Moss J, Henry J, Papadopoulou C, Mears SA. Hypohydration impairs endurance performance: a blinded study. Physiol Rep. 2017;5(12). pii: e13315.
65. Cheung SS, McGarr GW, Mallette MM, Wallace PJ, Watson CL, Kim IM, et al. Separate and combined effects of dehydration and thirst sensation on exercise performance in the heat. Scand J Med Sci Sports. 2015;25(Suppl 1):104–11.
66. Wall BA, Watson G, Peiffer JJ, Abbiss CR, Siegel R, Laursen PB. Current hydration guidelines are erroneous: dehydration does not impair exercise performance in the heat. Br J Sports Med. 2015;49(16):1077–83.
67. Adams JD, Sekiguchi Y, Suh HG, Seal AD, Sprong CA, Kirkland TW, et al. Dehydration impairs cycling performance, independently of thirst: a blinded study. Med Sci Sports Exerc. 2018. https://doi.org/10.14814/phy2.13315
68. Noakes TD. Lore of running. 4th ed. Champaign: Human Kinetics; 2003.
69. American College of Sports Medicine. Position statement of the American College of Sports Medicine: prevention of heat injuries during distance running. Med Sci Sports Exerc. 1975;7:vii–x.
70. Convertino VA, Armstrong LE, Coyle EF, Mack GW, Sawka MN, Senay LC Jr, et al. American College of Sports Medicine position stand. Exercise and fluid replacement. Med Sci Sports Exerc. 1996;28(1):i–vii.
71. Almond CS, Shin AY, Fortescue EB, Mannix RC, Wypij D, Binstadt BA, et al. Hyponatremia among runners in the Boston Marathon. N Engl J Med. 2005;352(15):1550–6.
72. Noakes TD, Sharwood K, Speedy D, Hew T, Reid S, Dugas J, et al. Three independent biological mechanisms cause exercise-associated hyponatremia: evidence from 2,135 weighed competitive athletic performances. Proc Nat Acad Sci USA. 2005;102(51):18550–5.
73. Noakes TD, Speedy DB. Case proven: exercise associated hyponatraemia is due to overdrinking. So why did it take 20 years before the original evidence was accepted? Br J Sports Med. 2006;40(7):567–72.
74. Noakes TD. Changes in body mass alone explain almost all of the variance in the serum sodium concentrations during prolonged exercise. Has commercial influence impeded scientific endeavour? Br J Sports Med. 2011;45(6):475–7.
75. Noakes T. Waterlogged: the serious problem of overhydration in endurance sports. Champaign: Human Kinetics; 2012.
76. Lewis D, Blow A, Tye J, Hew-Butler T. Considering exercise-associated hyponatraemia as a continuum. BMJ Case Rep. 2018. pii: bcr-2017-222916.
77. Kenefick RW. Drinking strategies: planned drinking versus drinking to thirst. Sports Med. 2018;48(Suppl 1):31–7.
78. Valenzuela PL, Morales JS, de la Villa P, Lucía A. Comment on: “drinking strategies: planned drinking versus drinking to thirst”. Sports Med. 2018. https://doi.org/10.1007/s40279-018-0905-5. [Epub ahead of print].
79. Daries HN, Noakes TD, Dennis SC. Effect of fluid intake volume on 2-h running performances in a 25 degrees C environment. Med Sci Sports Exerc. 2000;32:1783–9.

80. Dion T, Savoie FA, Asselin A, Gariepy C, Goulet ED. Half-marathon running performance is not improved by a rate of fluid intake above that dictated by thirst sensation in trained distance runners. Eur J Appl Physiol. 2013;113:3011–20.
81. Berkulo MA, Bol S, Levels K, Lamberts RP, Daanen HA, Noakes TD. Ad-libitum drinking and performance during a 40-km cycling time trial in the heat. Eur J Sport Sci. 2016;16:213–20.
82. Dugas JP, Oosthuizen U, Tucker R, Noakes TD. Rates of fluid ingestion alter pacing but not thermoregulatory responses during prolonged exercise in hot and humid conditions with appropriate convective cooling. Eur J Appl Physiol. 2009;105:69–80.
83. Bardis CN, Kavouras SA, Adams JD, Geladas ND, Panagiotakos DB, Sidossis LS. Prescribed drinking leads to better cycling performance than ad libitum drinking. Med Sci Sports Exerc. 2017;49:1244–51.