

Nutrition for Ultramarathon Running: Trail, Track, and Road

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Ultramarathon running events and participation numbers have increased progressively over the past three decades. Besides the exertion of prolonged running with or without a loaded pack, such events are often associated with challenging topography, environmental conditions, acute transient lifestyle discomforts, and/or event-related health complications. These factors create a scenario for greater nutritional needs, while predisposing ultramarathon runners to multiple nutritional intake barriers. The current review aims to explore the physiological and nutritional demands of ultramarathon running and provide general guidance on nutritional requirements for ultramarathon training and competition, including aspects of race nutrition logistics. Research outcomes suggest that daily dietary carbohydrates (up to $12 \text{ g}\cdot\text{kg}^{-1}\cdot\text{day}^{-1}$) and multiple-transportable carbohydrate intake ($\sim 90 \text{ g}\cdot\text{hr}^{-1}$ for running distances $\geq 3 \text{ hr}$) during exercise support endurance training adaptations and enhance real-time endurance performance. Whether these intake rates are tolerable during ultramarathon competition is questionable from a practical and gastrointestinal perspective. Dietary protocols, such as glycogen manipulation or low-carbohydrate high-fat diets, are currently popular among ultramarathon runners. Despite the latter dietary manipulation showing increased total fat oxidation rates during submaximal exercise, the role in enhancing ultramarathon running performance is currently not supported. Ultramarathon runners may develop varying degrees of both hypohydration and hyperhydration (with accompanying exercise-associated hyponatremia), dependent on event duration, and environmental conditions. To avoid these two extremes, euhydration can generally be maintained through “drinking to thirst.” A well practiced and individualized nutrition strategy is required to optimize training and competition performance in ultramarathon running events, whether they are single stage or multistage.

Keywords: carbohydrate, energy requirement, fat oxidation, gastrointestinal, hydration, protein

Ultramarathon running events and participation numbers have increased progressively over the past three decades ([Deutsche Ultramarathon Vereinigung, 2018](#)). Anecdotally, there has been growing interest from both amateur and elite endurance runners looking for new adventurous courses and challenges resulting in a wide range of competitive levels among ultramarathon participants, which also includes the substantial growing numbers of recreational ultramarathon participants targeting pleasure, tourism, health, and well-being outcomes. The increased participation has resulted in the internationalization of ultramarathon and trail running events, with established championship races (www.iaaf.org/disciplines/ultra-running/ultra-running). Ultramarathons are defined as running events longer than the traditional marathon and are hosted on trail, track, or road. Most are, however, performed as trail events and are typically either distance or time

specific ([Hoffman et al., 2010](#)). Trail running constitutes any off-road running event and can range from short distance fun runs to ultramarathon distance competitions. By nature, trail running is often associated with more harsh and challenging course topography (e.g., large elevation and descent, irregular running surfaces, and obstacles) and environmental conditions (e.g., cold, heat, humidity, and altitude) compared with track and road-based endurance running events and may require running with a loaded pack (i.e., day pack or self-sufficient load).

Another ultramarathon category is the multistage event, which has fixed distances or running time periods over multiple and consecutive days. Such ultramarathon types can be classified as either semisupported (i.e., event organizers transport participants' necessities between stages, with ad libitum food and fluid provisions) or self-sufficient (i.e., runners must carry all necessities, with minimal food requirement regulations [$\geq 2,000 \text{ kcal}\cdot\text{day}^{-1}$] and water ration provisions [$\sim 12 \text{ L}\cdot\text{day}^{-1}$]) and are normally accompanied by harsh trail course topographies; challenging environmental conditions (e.g., subzero, hot humid climates $\geq 30.0^\circ \text{C}$ with 50–90% relative humidity, and altitude attainment of $\geq 3,000 \text{ m}$); loaded running (e.g., up to 15 kg pack weight); and rough sleeping conditions (e.g., confined and/or crowded, unfamiliar, indoor or outdoor floor, tent, bivouac shelter or hammock). These additional challenges may contribute to the difficulty of multistage ultramarathon events, suggesting that lifestyle and mental management strategies (i.e., self-preservation, emotional adaptation, and ability

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hot (e.g., ≥ 30 °C) and humid (e.g., $\geq 80\%$ relative humidity) ambient conditions. The increased production of internal body heat during prolonged strenuous running, concomitant with external heat stress from the environment, can challenge thermoregulation mechanisms of ultramarathon runners. For example, it is well established that greater physiological and psychophysiological disturbances, prompted by thermoregulatory strain, are seen during running in ≥ 30 °C (with $\sim 20\%$ relative humidity) compared with temperate ambient conditions (Costa et al., 2014a; Snipe et al., 2018). Therefore, success in ultramarathon running events conducted in hot ambient conditions, irrespective of humidity, requires an ability to maintain homeostatic core body temperature via thermoregulatory and/or cooling strategies (e.g., heat acclimatization/acclimation, internal cold fluid intake and/or external body cooling), and/or maintaining euhydration (Brown & Connolly, 2015; Stevens et al., 2017). Nevertheless, given the lower exercise intensity of ultramarathon running, compared with shorter endurance running events, the risk of developing heat exhaustion is also lower (American College of Sports Medicine et al., 2007). However, ultramarathon runners are still at risk of heat stroke (i.e., gastrointestinal and systemic immune response pathophysiology), with clinical or subclinical issues potentially determined by running duration and magnitude of ambient heat exposure (Epstein et al., 2015; Gill et al., 2015).

Sleep deprivation is another common element of ultramarathon events that may influence performance outcomes. Evening or night scheduled event start times, organized overnight single-stage events or overnight stages within multistage events, ultramarathon events lasting >24 hr, and potentially rough sleeping arrangements may disturb sleep quantity and quality. Laboratory controlled trials have shown that sleep deprivation adversely impacts running performance, compared with a full night of restful sleep, albeit in a 30-min running distance test (Oliver et al., 2009). How these outcomes translate into the field setting within ultramarathon competitions is not clear, since there exists substantial intraindividual and interindividual variations in sleep quantity and quality within and between events (Martin et al., 2018).

Unlike shorter endurance running events, it is clear that the physiological demands of both single-stage and multistage ultramarathon participation vary considerably. These demands constitute both internal (e.g., physiological capabilities) and external (e.g., course topography, environmental conditions, and/or lifestyle management) factors, which can differ widely among ultramarathon events.

Nutritional Demands and Support Strategies

Information on the metabolic needs of ultramarathon runners is obtained largely from either extrapolations or indirect estimates using a variety of methods (e.g., equations, heart rate responses, and/or accelerometry), predominantly from either single-case or case-series research designs (Williamson, 2016). Nevertheless, total caloric expenditure rates, using validated accelerometry and/or breath-by-breath indirect calorimetry methodologies, appear to be positively associated with overall exertional stress (Vernillo et al., 2017; Williamson, 2016). Data have shown caloric expenditure of 3,831–4,999 kcal·day⁻¹ during a 225 km 5-day undulating multistage ultramarathon conducted in hot ambient conditions (Costa et al., 2013a), 4,764–5,654 kcal·day⁻¹ during a 305 km 8-day mountain based multistage ultramarathon conducted in cold to temperate ambient conditions (Britton et al., 2011), 6,000–8,000 kcal·day⁻¹ during a 250 km 5-day multistage ultramarathon laboratory

simulation (Alcock et al., 2018), and up to 18,000 kcal·day⁻¹ for a 24-hr single-stage trail ultramarathon (coverage range: 122–208 km) event (Costa et al., 2014b). These data suggest that single-stage ultramarathon events may result in a vast energy expenditure; however, at a relatively low continuous hourly rate (e.g., ~ 550 kcal·hr⁻¹ over a 24-hr period), with the total energy cost dependent on the specific race distance/time (Costa et al., 2014b; Williamson, 2016).

Considering the typically longer nonstop distance of single-stage ultramarathon events, compared with each individual stage of multistage ultramarathon events and subsequent nonexercising rest periods between stages, it is likely to be more difficult for ultramarathon runners to match energy expenditure with energy intake during single-stage ultramarathon competitions, resulting in a substantial acute energy deficit (Costa et al., 2014b; Enqvist et al., 2010; Martinez et al., 2018). Multistage ultramarathon events may present longer total distance coverage, but the segmentation of distance covered per day allows the opportunity for nutrition management and the provision for full requirements even with pack weight restrictions (e.g., ≤ 15 kg; Alcock et al., 2018). A closer match between energy expenditure and intake, especially carbohydrate provisions, is associated with better performance outcomes and less physiological disturbances (Alcock et al., 2018; Costa et al., 2013a, 2014b; Eden & Abernethy, 1994). Moreover, with increased food and fluid volume, in order to reduce the energy deficit gap, there is a potential risk of developing exercise-associated gastrointestinal symptoms due to compromised gastrointestinal function (i.e., delayed gastric emptying and intestinal transit, impaired digestion and intestinal absorption) consistently observed in response to exercise stress per se (Costa et al., 2017a, 2017b; Horner et al., 2015; Leiper, 2015). However, it appears that training status may influence food and fluid intake tolerance during running, since highly trained runners display lower gastrointestinal intolerance and symptoms during endurance running compared with recreational counterparts at the same relative running intensity, duration, and carbohydrate challenge dose (Costa et al., 2017a). It is suggested that these observations may be associated with practicing race nutrition during training at the elite level of competition. From a practical perspective, ultramarathon runners should experiment with different degrees of food and fluid quantities and qualities (i.e., liquid, semisolid, and solids) to ascertain individual upper limits of gastrointestinal tolerance and preferences.

Meeting energy demands, and subsequent macronutrient profile and micronutrient provisions, for general ultramarathon running training and multistage ultramarathon events appears to be manageable with appropriate planning, as per general endurance exercise consensus guidelines (Thomas et al., 2016). For consecutive days of prolonged endurance running, achieving energy balance is recommended, alongside the provision of sufficient carbohydrate to meet exercise load demands (i.e., up to 12 g·kg⁻¹·day⁻¹, total running load dependent), and consumption of sufficient protein to meet daily nitrogen balance (i.e., 1.2–2.0 g·kg⁻¹·day⁻¹), to support tissue recovery and adaptations (Phillips & van Loon, 2011; Tamopolsky et al., 1988). Habitual dietary protein needs for elite endurance athletes are estimated to be 1.6–1.8 g·kg⁻¹·day⁻¹ (Kato et al., 2016; Tamopolsky et al., 1988), and such a requirement is likely to be similar for ultramarathon runners, given similar training volumes. In contrast, consuming this amount of dietary protein during single-stage ultramarathon running events is unlikely to be possible for most runners, especially if unsupported (Kato et al., 2016). For example, elite 100-mile ultramarathon runners consume very little protein before or during competition (Stellingwerff, 2016). However, 1.3–2.2 g·kg⁻¹·day⁻¹ of protein has

been observed in successful semisupported and self-sufficient multi-stage ultramarathon finishers (Costa et al., 2013a; McCubbin et al., 2016). Although the coingestion of protein with carbohydrate during exercise does not appear to improve endurance exercise performance in activities <2 hr in duration (Beelen et al., 2011; Cermak et al., 2009), there is an improvement in net protein balance with protein and carbohydrate versus carbohydrate alone in a 6-hr ultra-endurance trial (Koopman et al., 2004), and it would be of interest to see if this enhances ultramarathon running performance. Fat intake supports the provision of additional daily energy requirements, usually 20–35% of total daily energy intake/requirements. Further limiting fat intake has not proven beneficial for performance outcomes and risks overall nutritional inadequacy (e.g., fat soluble vitamins and essential fatty acids).

With regard to specific macronutrient intake and timing, 1–4 g·kg⁻¹ of carbohydrate 1–4 hr before endurance running is recommended (Thomas et al., 2016). This is particularly beneficial when carbohydrate intake within the recovery period between running bouts fails to fully restore muscle glycogen storage, and in addition supports glucose availability during the initial phase of exercise. The choice of food and/or fluid to be consumed during the preexercise period should focus on avoiding potential gastrointestinal discomfort and/or intolerance (e.g., low in fat, protein, fiber, and fermentable oligo- di- monosaccharides and polyol content; Lis et al., 2019). Immediately after prolonged strenuous running, the consumption of 1.0–1.2 g·kg⁻¹ of carbohydrate is recommended to assist muscle glycogen resynthesis, with some additional protein (up to 0.3–0.4 g·kg⁻¹) to aid tissue recovery (Beelen et al., 2010).

Although the nutritional intake to meet the demands of shorter endurance running events seems feasible, evidence suggests that competitive ultramarathon runners find these nutritional recommendations hard to implement on an ad libitum basis, especially during the competition phase (Costa et al., 2013a, 2014b; Heaney et al., 2011). Excessive transient or long-term low-grade energy (and nutritional) deficits justify considering ultramarathon runners as a high-risk population for the development of relative energy deficiency syndrome (including the female triad), unexplained underperformance (overtraining) syndrome, exercise-induced gastrointestinal syndrome, soft tissue injuries and illnesses/infections, with associated acute and chronic health implications of clinical significance (Costa et al., 2017b; Lewis et al., 2015; Mountjoy et al., 2018; Schwellnus et al., 2016; Soligard et al., 2016).

Considering nutritional recommendations for general endurance exercise are predominantly derived from controlled laboratory settings, generally among highly trained individuals, differing modalities (e.g., endurance cycling), and distances shorter than in typical ultramarathon running; it is plausible that these current recommendations may need adjusting to cater for the specific population demographics, real life practical barriers, and specific race characteristics. Further research is warranted in this area, including the comprehensive and accurate assessment and analysis of the nutrition protocols of successful ultramarathon runners and comparison against recommendations for endurance exercise and the role of prescriptive energy and nutrient intake templates on markers of fuel kinetics, physiological and psychophysiological disturbance markers, symptomatology, and performance outcomes.

Fat Adaptation Protocols

In recent years, anecdotal evidence from sport nutrition professionals suggests a growing number of elite and amateur ultramarathon runners are purposely attempting, with or without professional guidance,

adherence to low-carbohydrate high-fat (LCHF) or ketogenic diets, aiming to enhance maximal and relative fat oxidation capacity during moderate–vigorous running speeds, and subsequently to enhance ultramarathon running performance. This growing dietary trend among ultramarathon runners occurs despite scarce research supporting performance improvement with these dietary interventions (Pinckaers et al., 2017).

Fat is a favorable fuel substrate during low- and moderate-intensity running, and/or when endogenous muscle glycogen stores become depleted. It is well established that fat oxidation, at a given running intensity, can be upregulated by appropriate training, or in response to dietary carbohydrate and fat manipulations (Burke, 2015; Impey et al., 2016; Pinckaers et al., 2017). Theoretically, ultramarathon runners with high fat oxidation rate adaptations (e.g., ≥1.2 g/min) could sustain ~700 kcal/hr of energy from fat oxidation alone, which may be beneficial if running duration is prolonged (e.g., ≥10 hr), and of low (i.e., walking pace at 5–6 km·hr⁻¹; equivalent to ~45% $\dot{V}O_{2\max}$) to moderate (i.e., 8–12 km·hr⁻¹; equivalent to 55–70% $\dot{V}O_{2\max}$) intensity (Alcock et al., 2018; Costa et al., 2013a, 2014a, 2014b, 2017a; Rauch et al., 2018; Snipe et al., 2018). From an ultramarathon perspective, higher exercise intensities (i.e., >70% $\dot{V}O_{2\max}$) could intermittently occur with undulating or extreme course topographies, and/or while managing course obstacles (Balducci et al., 2017; Degache et al., 2016; Fornasiero et al., 2018; Kerhervé et al., 2015; Vernillo et al., 2017), which may not be sufficiently fueled by utilization of fat energy substrate alone.

There is considerable debate about whether an ultramarathon runner might have a performance benefit from dietary carbohydrate or fat manipulations, ketogenic adaptation, or simply training in a glycogen depleted state to enhance fat oxidation (Burke, 2015; Impey et al., 2016; Pinckaers et al., 2017). Indeed, such dietary behavior has consistently shown increased peak fat oxidation rates at exercise intensities between 60% and 80% $\dot{V}O_{2\max}$ (1.5–1.8 g/min; Burke et al., 2017; Volek et al., 2016). However, high fat oxidation rates also appear to be inherent in ultramarathon runners regardless of background macronutrient dietary modifications. A recent study ($n = 15$ men) found a wide range of maximal fat oxidation rates (mean: 68% (95% confidence interval [61–74%] $\dot{V}O_{2\max}$) and steady-state fat oxidation rates (0.8–1.7 g/min) over 3 hr of running at 60% $\dot{V}O_{2\max}$ (mean \pm SD: 10.0 \pm 1.2 km·hr⁻¹), while adhering to a macronutrient balanced diet (20% protein, 52% carbohydrate, and 28% fat) and consuming carbohydrates during exercise (90 g/hr, 2:1 glucose–fructose 10% wv; Rauch et al., 2018).

Determining whole-body fuel utilization during ultramarathon events presents challenges and complexities, which will impact on the magnitude of exercise stress, and subsequently dictate fuel kinetics (Howe et al., 2018). Although a comprehensive evaluation of dietary manipulation in ultramarathon runners has not yet been completed, positive correlations of preexercise dietary carbohydrate manipulations and during running and carbohydrate intake with performance outcomes are consistently observed in endurance models, which may be applicable to ultramarathon runners (Smith et al., 2013; Stellingwerff & Cox, 2014). Further research is needed, however, to investigate the potential role of dietary carbohydrate and fat manipulations specific to ultramarathon running performance.

Race Nutrition

Logistics

Due to the wide variation in ultramarathon events, the logistics of race nutrition management vary dramatically. In some events, few

supplies are needed and can be accommodated by a handheld water bottle, soft flask, or small pack with water bladder, with minimal nutritional items carried in pack, clothing pockets, and/or waist band. In contrast, other events require a larger pack to carry mandatory gear, multiple days of food, equipment, and other necessities, as well as the ability to carry sufficient water for consecutive hours of running and/or a means of water purification. However, some general factors appropriate for all events can be considered.

Energy intake ranging from 36% to 63% of energy expenditure have been reported in continuous single-stage ultramarathon events lasting from 24 to 30 hr (Costa et al., 2014b; Stuempfle et al., 2011). Energy deficits of $>1,000$ kcal·day⁻¹ have been seen in semisupported and self-sufficient multistage ultramarathon competitions (Costa et al., 2013a; McCubbin et al., 2016). With this in mind, ultramarathon runners are unlikely to fully replace energy expenditure acutely and need not plan on carrying full energy requirements. Alternatively, they should strive to logistically organize and consume what is feasibly tolerable (Table 1).

Avoiding an excessive energy deficit is best accomplished with nutrient dense foods and fluids, which have been consumed in training that mimics race conditions, and is adequately tolerated. To avoid carrying excessive amounts of nutritional items during the event and therefore unnecessary pack weight, ultramarathon runners should determine in advance which nutritional items will be available during the event and assess such items in training. Furthermore, it is important to determine whether certain foods are available in the race country, since local choices can vary widely. Regardless of this, appetite dysfunction, taste fatigue, and gastrointestinal symptoms are common during ultramarathon events (Costa et al., 2016; Hoffman & Fogard, 2011), so runners should be flexible to the nutritional items consumed by conceding to cravings or what appears most tolerable. Finally, if nutrients are being largely or exclusively consumed in liquid form, caution should be taken to avoid hyperhydration and associated health complications (e.g., hyponatremia).

Feeding During Running

It is well established that carbohydrate consumption during exercise enhances endurance performance (Smith et al., 2013; Stellingwerff & Cox, 2014). Research that has formed the basis for feeding during endurance exercise consensus guidelines and recommendations (Thomas et al., 2016), predominantly used experimental designs less than the marathon distance/time and/or other modalities (e.g., cycling; Smith et al., 2013; Stellingwerff & Cox, 2014). Nevertheless, for ultramarathon running, whereby duration is typically >4 hr, it is generally recommended to consume 90 g·kg⁻¹ of a multiple-transportable carbohydrate blend (e.g., 2:1 glucose–fructose ratio; Thomas et al., 2016). Gastric emptying, intestinal transit, and nutrient absorption in response to exertional stress, together with blood glucose availability, glucose muscle uptake, and oxidation capacity, are influential factors in an individual's ability to tolerate and utilize exogenous carbohydrates during exercise (Costa et al., 2017a; Cox et al., 2010; Horner et al., 2015; Leiper, 2015). It appears that such high levels of carbohydrate intake during running are not achievable by the majority of both elite and amateur ultramarathon runners (Costa et al., 2016). For example, ad libitum carbohydrate intake rates during running in single-stage and multistage ultramarathon events are consistently reported between 20 and 40 g·hr⁻¹, despite reports of runners carrying >60 g·hr⁻¹ (Costa et al., 2013a, 2014; Kruseman et al., 2005; Martinez et al., 2018; Stuempfle et al., 2011). During various distances of the Ultra Mallorca Serra de Tramuntana, Spain, and a 44-km mountain ultramarathon in Switzerland, $>50\%$ of participants failed to consume >30 g·hr⁻¹ of carbohydrate (Kruseman et al., 2005; Martinez et al., 2018).

Given that general aerobic fuel oxidation rates for ultramarathon running have not yet been fully explored, applying the guidelines and recommendations for shorter endurance exercise could be erroneous. Therefore, individual specific assessment for carbohydrate gastric emptying and intestinal transit, digestibility and absorbability, and oxidation rates during exercise stress is recommended. For example, assessment might include: ¹³C labeled

Table 1 Example Dietary Plan for Semisupported and Self-Sufficient Multistage Ultramarathon Competition

Target energy intake and weight ^a	3,000–4,000 kcal Approximate food weight: 0.8 kg	4,000–5,000 kcal Approximate food weight: 1.1 kg	5,000–6,000 kcal Approximate food weight: 1.3 kg	6,000–7,000 kcal Approximate food weight: 1.5 kg
Breakfast	Dehydrated/freeze-dried cereal meal ^b	Dehydrated/freeze-dried cereal meal ^b	Dehydrated/freeze-dried cereal meal ^b	Dehydrated/freeze-dried cereal meal ^b
During running	Tolerable carbohydrate intake during exercise ^c	Tolerable carbohydrate intake during exercise ^c	Tolerable carbohydrate intake during exercise ^c	Tolerable carbohydrate intake during exercise ^c
Recovery	Recovery beverage ^d	Recovery beverage ^d	Recovery beverage ^d	Recovery beverage ^d
		Dehydrated/freeze-dried savory meal ^b	Dehydrated/freeze-dried savory meal ^b	Dehydrated/freeze-dried savory meal ^b
Afternoon snack	Portion of trail mix with dried fruit and nuts (100 g)	Portion of trail mix with dried fruit and nuts (100 g)	Portion of trail mix with dried fruit and nuts (100 g)	Dehydrated/freeze-dried sweet snack ^b Portion of trail mix with dried fruit and nuts (100 g)
Evening meal	Dehydrated/freeze-dried savory meal ^b	Dehydrated/freeze-dried savory meal ^b	Dehydrated/freeze-dried savory meal ^b Recovery beverage ^d	Dehydrated/freeze-dried savory meal ^b Recovery beverage ^d
Supper	Pretzel portion (60 g)	Pretzel portion (80 g)	Dehydrated/freeze-dried sweet snack ^b	Dehydrated/freeze-dried sweet snack ^b

Note. ^aEstimations based on 10–15% protein, 70–75% carbohydrate, and 10–20% fat energy contribution. Does not include water (i.e., hydration needs). ^bNutritional value based on standard dehydrated/freeze-dried meal averages. ^cApproximately 0.8–1.0 g·kg⁻¹·hr⁻¹ carbohydrate, in a 6–10% wv solution (Costa et al., 2017a). ^d1.2 g/kg carbohydrate and 0.4 g·kg⁻¹ protein, in a 10% carbohydrate wv solution (Beelen et al., 2010).

food or fluid ingestion or lactulose challenge followed by breath sampling and analysis with or without electrogastrography to assess gastrointestinal transit functional responses; specific (i.e., quantity and quality) food or fluid challenge with breath sampling and analysis to quantify H_2 and CH_4 concentration to assess feeding tolerance and magnitude of malabsorption; breath-by-breath indirect calorimetry to assess total carbohydrate oxidation rates at the point of stressed muscle glycogen stores (e.g., ≥ 3 hr running at 55–70% $\dot{V}O_{2\max}$). Test-Retest Reliability of a Modified Visual Analog Scale Assessment Tool for Determining Incidence and Severity of Gastrointestinal Symptoms in Response to Exercise Stress (Costa et al., 2017a, 2017b; Gaskell, Snipe, & Costa, 2019; Gill et al., 2015; Snipe et al., 2018), and the outcomes could be integrated into competition nutrition plans (Table 2). However, the proposed high rates of 90 g·hr⁻¹ of a multiple-transportable carbohydrate blend for endurance exercise ≥ 3 hr probably requires scaling down for ultramarathon activities, due to the lower absolute exercise intensity (Jeukendrup, 2014).

Gastrointestinal Disturbance and Symptoms

Gastrointestinal symptoms are a common feature of ultramarathon running, with a 60–96% prevalence of severe symptoms reported after ultramarathon competition (Costa et al., 2017b). Gastrointestinal symptoms have been reported as a major factor limiting nutritional intake during and after ultramarathon events, withdrawal from competition, and are linked to severe clinical episodes of acute colitis with accompanying fecal blood loss (Costa et al., 2016, 2017b). The causes of adverse gastrointestinal symptoms during and after ultramarathon running appear to be multifactorial in nature but are likely related to splanchnic hypoperfusion and increased sympathetic drive, which results in clinically significant secondary outcomes, such as epithelial injury and permeability; impaired gastrointestinal function; and systemic responses (i.e., endotoxemia and cytokinemia), termed “exercise-induced gastrointestinal syndrome” (Costa et al., 2017b). The management of extrinsic (e.g., magnitude of exercise stress and coping with

environmental conditions) and intrinsic (e.g., feeding tolerance and underlying gastrointestinal conditions) exacerbating factors appears to be the first line action against exercise-induced gastrointestinal syndrome and associated symptoms. Certain dietary strategies before and/or during exercise may be beneficial, favorable, neutral, or damaging in supporting gastrointestinal integrity and function during exercise stress models (Figure 2). However, an individualized approach, after gastrointestinal assessment and tolerance measurements during running, is essential for the efficacious prevention and/or management of exercise-induced gastrointestinal syndrome in ultramarathon runners.

Hydration

Proper management of hydration is critical for both performance and overall health in ultramarathon running. However, it is apparent that there are many challenges facing ultramarathon runners in managing hydration, as evident from observations at a 161-km ultramarathon, in which 10% of participants gained body mass and 7% were hyponatremic at the finish (Hoffman & Stuenkel, 2015). Similar hydration mismanagement has been observed during multistage and 24-hr ultramarathon events (Costa et al., 2013b, 2014b). The present review will focus on aspects of hydration unique to ultramarathon participation (Table 3), which may vary in comparison with hydration needs of shorter endurance running events (see Casa et al., in press).

During the hours or days of running while participating in ultramarathon events, proper hydration involves maintaining adequate fluid intake to avoid performance limiting hypohydration, while also avoiding excessive fluid intake with potential for developing exercise-associated hyponatremia (EAH; Hew-Butler et al., 2015). Endurance exercise performance has been reported to be impaired with 1–2% total body water loss in controlled laboratory studies (Sawka et al., 2001). However, it has been suggested that such conditions do not necessarily translate into field-based scenarios (Wall et al., 2015) and must be interpreted with recognition that changes in body water and body mass are not equivalent

Table 2 Practical Nutrition Recommendations to Support Individualized Strategies During Participation in Ultramarathon Running Events

Nutrition—practical recommendations

- Trial and practice race nutrition in training sessions, including specific food and fluid quality and quantity.
- Experiment with different fluid volumes, and carbohydrate intake rates and concentrations, and find the optimal individualized tolerance levels. Increasing fluid volume first, then try increasing carbohydrate concentration.
- Experiment with different carbohydrate types (e.g., blends such as glucose–fructose) and forms (e.g., fluids, gels, bars, puree, fruits, and other carbohydrate-rich foods).
- Undertake a gastrointestinal assessment during running in a competition mirrored simulation to establish individual tolerance to carbohydrate types, forms, and concentrations.
- Alter the acute rate of intake (e.g., small and frequent intake), and experiment with higher intake rates early into running, since gastrointestinal symptoms are generally lower during the first 2 hr of running and then start to develop thereafter.
- Practice race nutrition strategies in less important ultramarathon running events to try and identify “outside” contributing factors (e.g., travel effects, competition stress, changes in habitual food availability, weather conditions, and pacing).
- Identify the food and fluid provisions (including bottled water) of each ultramarathon event participation, and experiment with these both chronically (throughout the day) and during exercise. This is especially important to consider when racing away from the home base (e.g., nationally or internationally).
- In longer races (≥ 8 hr) experiment with various easily digestible and carbohydrate-rich solid food sources. Avoid foods excessively rich in protein, fat, fiber, and fermentable oligo- di- monosaccharides and polyols.
- In longer races (≥ 8 hr), in cases where tolerance to carbohydrate intake and gastrointestinal symptoms are an issue, mouth rinsing with a carbohydrate beverage may support the maintaining of workload through the oral cortex sensory network.

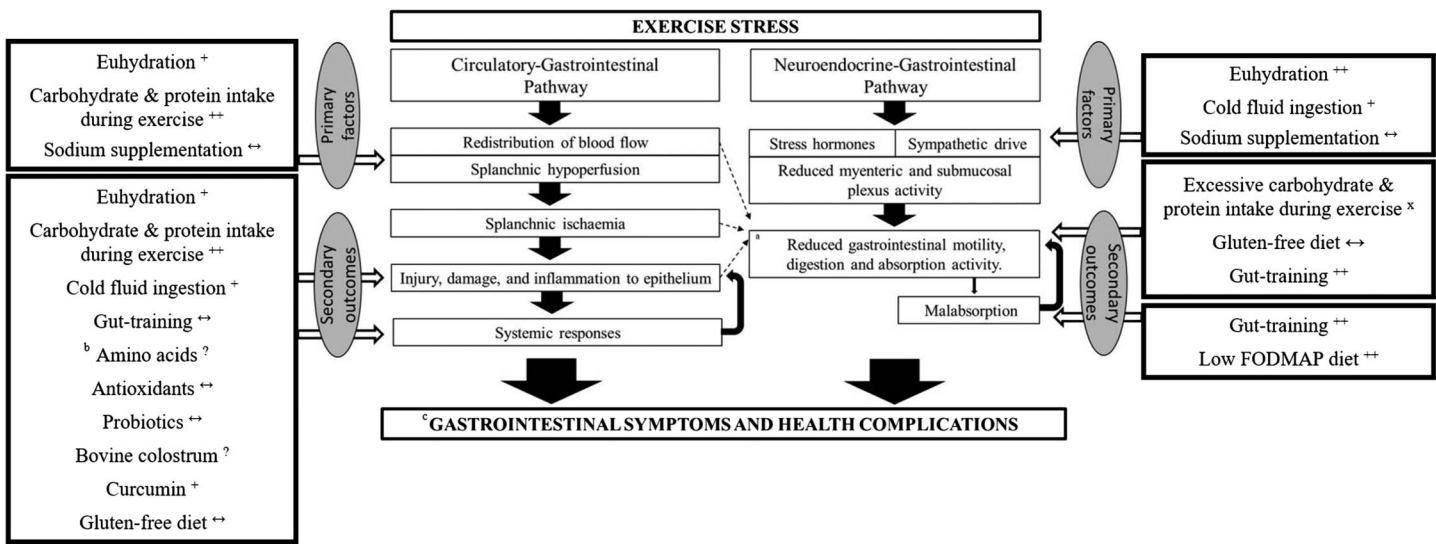


Figure 2 — Schematic description of updated evidence for dietary modification and nutritional supplement interventions for the prevention and management of exercise-induced gastrointestinal syndrome. Adapted from Costa et al. (2017b) with permission. ++Evidence of substantial beneficial effect; +evidence of beneficial effect, but modest in nature; ↔none or insufficient evidence of beneficial effect; ?inconclusive, unknown, and (or) conflicting efficacy. ^aSplanchnic hypoperfusion, and subsequent intestinal ischemia and injury (including mucosal erosion) results in direct (e.g., enteric nervous system and/or enteroendocrine cell) or indirect (e.g., nutrient malabsorption) alterations to gastrointestinal motility. ^bAmino acids glutamine, L-arginine, and L-citrulline. ^cGastrointestinal symptoms include: upper (gastroesophageal and gastroduodenal originated: regurgitation, urge to regurgitate, gastric bloating, belching, stomach pain, and heartburn/gastric acidosis) and lower (intestinal originated: flatulence including lower abdominal bloating, urge to defecate, abdominal pain, abnormal defecation including loose water stools, diarrhea, and blood in stools) gastrointestinal symptoms, and/or other-related symptoms (e.g., nausea, dizziness, and acute transient abdominal pain).

Table 3 Practical Hydration Recommendations to Support Individualized Strategies During Participation in Ultramarathon Running Events

Hydration—practical recommendations
<ul style="list-style-type: none">• Initiate exercise in an euhydrated state and avoid preexercise hyperhydration.• During running “drink to thirst” using “ad libitum” drinking strategies, provided fluids are available.• Avoid excessive volumes of fluid intake, know fluid tolerance limits. Small and frequent limit gastric overload during a period of compromised gastrointestinal function.• Avoid excessive sodium supplementation during running. Consume sodium based on food cravings. Do not use highly visible salt losses as a signal for increasing sodium intake.• When fluid access is limited and must be carried by the runner between sources, estimating fluid needs is best done through experience or through training or laboratory conditions to assess the range of potential requirements, while recognizing that the appropriate fluid intake will vary with course topography, ambient conditions, and pacing.• Determining hydration status is best achieved through history of fluid intake and monitoring body mass, recognizing that some body mass will be lost during prolonged exercise as a result of oxidation of endogenous fuel stores, water generation with fuel oxidation, and the release of water bound to glycogen during glycogenolysis.• If training and/or competing in hot ambient conditions (both dry and humid), prior heat acclimatization/acclimation is valuable as it results in plasma volume expansion.• Oliguria (limited urine output) is not necessarily a sign of dehydration. Avoid using urine measures of hydration (e.g., urine color, urine specific gravity, and urine osmolality) as a method of monitoring hydration status during ultramarathon running activities.

(Hoffman et al., 2018a; Maughan et al., 2007). On the other hand, hyperhydration is the primary risk for the development of EAH, from which a number of fatalities have been reported during various activities (Hew-Butler et al., 2015). Fortunately, to date, we are unaware of any EAH-related deaths in ultramarathon events. Hyperhydration can also decrease performance indirectly by increasing body mass and unnecessary fluid carrying, time delays for drinking and filling fluid containers, and pauses required for urination. In addition, excess fluid intake may result in an

overwhelming gastric load (i.e., increase intragastric pressure) and contribute to upper gastrointestinal symptoms (Costa et al., 2019; Leiper, 2015). Thus, avoiding hyperhydration or hypohydration is recommended for both health and performance in ultramarathon running. Proper hydration during ultramarathon running requires the understanding that all fluid losses need not be replaced, as body mass loss from endogenous substrate oxidation is expected (Hoffman et al., 2018a; Maughan et al., 2007). It is also recognized

that water is produced during fuel oxidation and that some water linked with glycogen may be released in response to oxidation of endogenous glycogen stores. However, the extent of availability of these water sources to support the intravascular water pool remains controversial, and the proper proportion of body mass loss during endurance running is not completely clear. Nonetheless, if the running bout is long enough, the desired body mass loss will be beyond the typical guidelines suggesting that losses should be limited to no more than 2% of body mass (McDermott et al., 2017).

Many authorities now consider “drinking to thirst” (also referred to as *ad libitum* drinking) to be the optimal strategy to assure proper hydration during endurance running (Hew-Butler et al., 2015; Hoffman et al., 2016, 2018b). On the contrary, others consider thirst to be an inadequate stimulus to maintain proper hydration (Armstrong et al., 2016). However, past recommendations emphasizing this were largely intended for situations in which dehydration might develop rapidly from high sweat rates associated with high exercise intensities (Hew-Butler et al., 2015), which is not applicable to moderate-intensity competitive ultramarathon running and large sections of walking (i.e., low-intensity exercise) in recreational ultramarathon participants. Indeed, considerable evidence has demonstrated that drinking to thirst during ultramarathons, even under hot ambient conditions (e.g., $\geq 30^{\circ}\text{C}$), supports adequate hydration (Costa et al., 2013b; Hoffman et al., 2018b; Hoffman & Stuempfle, 2014, 2016; Tam et al., 2011). Thus, adequate fluid intake during ultramarathon running can generally be achieved by simply drinking fluids *ad libitum*, as long as there is adequate access to fluids when desired. When fluid access is limited, it is essential for runners to estimate the fluid volume required to carry between sources to support thirst (i.e., balance availability with avoiding the need to carry unnecessary fluids). This is best done through experience, while recognizing variability in the appropriate fluid intake with exercise intensity and ambient conditions.

In conjunction with hydration strategies, sodium supplementation, before and during running, is a common practice among ultramarathon runners, owing to beliefs that sodium will prevent dehydration, muscle cramping, nausea, and EAH, and subsequently enhance performance (McCubbin & Costa, 2018; McCubbin et al., 2018). It has, however, been demonstrated that supplemental sodium is not necessary to maintain euhydration during ultramarathon competition, even under hot ambient conditions (Hoffman et al., 2015). Moreover, sodium intake during exercise will also not prevent EAH in the presence of hyperhydration (Hew-Butler et al., 2015). Thus, best practice suggests avoiding attempts to replace all sodium lost in sweat through the intake of sodium supplementation during ultramarathon running, recognizing that considerable sodium is present in the typical race diet (e.g., electrolyte beverages, sports bars and gels, savory sandwiches, crisps, pretzels, and soups).

Conclusions

In comparison with shorter endurance running events, it is evident that the physiological demands, and subsequently the total nutritional and hydration demands, of ultramarathon running are far greater, and dependent on the event distance or time, course topography, environmental conditions, and degree of support and/or self-sufficiency. While considering nutrition and hydration guidelines and recommendations for general endurance exercise may provide some guidance and support for shorter running events and ultramarathon training, caution is warranted in using these guidelines for ultramarathon competition due to the large diversity of participant demographics and event characteristics. It is clear that individual

assessment to determine daily and event nutrition and hydration requirements, based on the runner’s specificities (e.g., physiology, tolerance, and preference) and event characteristics, is essential to inform appropriate customized nutritional action plans. It is unlikely that full energy and nutritional provisions can be met during single-stage and multistage ultramarathons; however, developing training and race nutritional strategies to ameliorate the potentially extreme deficit will support training and event performance, and also contribute to the prevention or attenuation of any associated health complications of subclinical or clinical significance.

Take Home Messages

- Aerobic capacity and lactate responses, running economy and skill, pacing strategies, exogenous and endogenous energy substrate availability and utilization kinetics, thermoregulation, gastrointestinal integrity and functional responses, lifestyle management, mental attitude, and cognitive function are important physiological and psychophysiological characteristics for performance success in ultramarathon competition.
- The physiological demands and subsequently nutritional requirements of ultramarathon running are greater than shorter track and road endurance running events.
- Consuming sufficient foods and/or fluids, within tolerance level, in the attempt to meet energy (and macronutrient) demands provides an efficacious base for optimal ultramarathon training and competition.
- The consumption of $1.6\text{--}1.8\text{ g}\cdot\text{kg}^{-1}\cdot\text{day}^{-1}$ of protein is likely to be sufficient for ultramarathon training. However, it is unclear what the amino acid or protein needs are during ultramarathon competition to optimize performance.
- Race nutrition management varies widely due to differences in ultramarathon events, but individual gastrointestinal tolerance, food–fluid availability, and preference will dictate the magnitude of an energy deficit during ultramarathon competition.
- Gastrointestinal assessment and tolerance measurements during running are essential for the application of appropriate feeding plans during running and management of exercise-induced gastrointestinal syndrome.
- Proper hydration during ultramarathon participation can generally be maintained by drinking to thirst.

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References

- Alcock, R., McCubbin, A., Camões-Costa, V., & Costa, R.J.S. (2018). Case study: Nutritional support for self-sufficient multi-stage

- ultra-marathon: Rationed versus full energy provisions. *Wilderness and Environmental Medicine*, 29(4), 508–520.
- American College of Sports Medicine, Armstrong, L.E., Casa, D.J., Millard-Stafford, M., Moran, D.S., & Pyne, S.W., (2007). American college of sports medicine position stand. Exertional heat illness during training and competition. *Medicine & Science in Sports & Exercise*, 39(3), 556–572.
- Armstrong, L.E., Johnson, E.C., & Bergeron, M.F. (2016). Counterintuitive: Is drinking to thirst adequate to appropriately maintain hydration status during prolonged endurance exercise? No. *Wilderness and Environmental Medicine*, 27(2), 195–198. PubMed ID: 27291700 doi:10.1016/j.wem.2016.03.002
- Balducci, P., Clemmenon, M., Trama, R., Blache, Y., & Hautier, C. (2017). Performance factors in a mountain ultramarathon. *International Journal of Sports Medicine*, 38(11), 819–826. PubMed ID: 28799161 doi:10.1055/s-0043-112342
- Beelen, M., Burke, L.M., Gibala, M.J., & van Loon, L.J.C. (2010). Nutritional strategies to promote postexercise recovery. *International Journal of Sport Nutrition and Exercise Metabolism*, 20(6), 515–532. PubMed ID: 21116024 doi:10.1123/ijnsnem.20.6.515
- Beelen, M., Zorenc, A., Pennings, B., Senden, J.M., Kuipers, H., & van Loon, L.J. (2011). Impact of protein coingestion on muscle protein synthesis during continuous endurance type exercise. *American Journal of Physiology—Endocrinology and Metabolism*, 300(6), E945–E954. PubMed ID: 21364122 doi:10.1152/ajpendo.00446.2010
- Bossi, A.H., Matta, G.G., Millet, G.Y., Lima, P., Pertence, L.C., de Lima, J.P., & Hopker, J.G. (2017). Pacing strategy during 24-hour ultra-marathon-distance running. *International Journal of Sports Physiology and Performance*, 12(5), 590–596. PubMed ID: 27618658 doi:10.1123/ijsp.2016-0237
- Britton, R., Dempster, S., Moore, J.P., & Costa, R.J.S. (2011). The use of triaxial accelerometry to support dietary intervention during a multi-stage mountain ultra-marathon: A case study approach. *Journal of Sport Science*, 29(Suppl 2), S132.
- Brown, J.S., & Connolly, D.A. (2015). Selected human physiological responses during extreme heat: The Badwater Ultramarathon. *Journal of Strength and Conditioning Research*, 29(6), 1729–1736. PubMed ID: 25463692 doi:10.1519/JSC.0000000000000787
- Burke, L.M. (2015). Re-examining high-fat diets for sports performance: Did we call the “nail in the coffin” too soon? *Sports Medicine*, 45(Suppl. 1), 33–49. doi:10.1007/s40279-015-0393-9
- Burke, L.M., Ross, M.L., Garvican-Lewis, L.A., Welvaert, M., Heikura, I.A., Forbes, S.G., . . . Hawley, J.A. (2017). Low carbohydrate, high fat diet impairs exercise economy and negates the performance benefits from intensified training in elite race walkers. *Journal of Physiology*, 595(9), 2785–2807. doi:10.1113/JP273230
- Casa, D.J., Chevront, S.N., Galloway, S.D., & Shirreffs, S.M. (2019). Fluid needs for training, competition, and recovery in track and field athletes. *International Journal of Sports Nutrition and Exercise Metabolism*, 29. doi:10.1123/ijnsnem.2018-0374
- Cermak, N.M., Solheim, A.S., Gardner, M.S., Tarnopolsky, M.A., & Gibala, M.J. (2009). Muscle metabolism during exercise with carbohydrate or protein-carbohydrate ingestion. *Medicine and Science in Sports and Exercise*, 41(12), 2158–2164. PubMed ID: 19915503 doi:10.1249/MSS.0b013e3181ac10bf
- Costa, R.J.S., Camões-Costa, V., Snipe, R.M.J., Dixon, D., Russo, I., & Huschtscha, Z. (2019). The impact of exercise-induced hypohydration on intestinal integrity, function, symptoms, and systemic endotoxin and inflammatory responses. *Journal of Applied Physiology*.
- Costa, R.J.S., Crockford, M.J., Moore, J.P., & Walsh, N.P. (2014a). Heat acclimation responses of an ultra-endurance running group preparing for hot desert based competition. *European Journal of Sports Science*, 14(S1), S131–S141. doi:10.1080/17461391.2012.660506
- Costa, R.J.S., Gill, S.K., Hankey, J., Wright, A., & Marczak, S. (2014b). Perturbed energy balance and hydration status in ultra-endurance runners during a 24 h ultra-marathon. *British Journal of Nutrition*, 112, 428–437. doi:10.1017/S0007114514000907
- Costa, R.J.S., Miall, A., Khoo, A., Rauch, C., Snipe, R., Camões-Costa, V., & Gibson, P. (2017a). Gut-training: The impact of two weeks repetitive gut-challenge during exercise on gastrointestinal status, glucose availability, fuel kinetics, and running performance. *Applied Physiology Nutrition and Metabolism*, 42(5), 547–557. doi:10.1139/apnm-2016-0453
- Costa, R.J.S., Snipe, R., Camões-Costa, V., Scheer, B.V., & Murray, A. (2016). The impact of gastrointestinal symptoms and dermatological injuries on nutritional intake and hydration status during ultramarathon events. *Sports Medicine- Open*, 2(16), 1–14.
- Costa, R.J.S., Snipe, R., Kitic, C., & Gibson, P. (2017b). Systematic review: Exercise-induced gastrointestinal syndrome—Implication for health and disease. *Alimentary Pharmacology and Therapeutics*, 46(3), 246–265. doi:10.1111/apt.14157
- Costa, R.J.S., Swancott, A., Gill, S., Hankey, J., Scheer, V., Murray, A., & Thake, D. (2013a). Compromised energy and nutritional intake of ultra-endurance runners during a multi-stage ultra-marathon conducted in a hot ambient environment. *International Journal of Sports Science*, 3(2), 51–61.
- Costa, R.J.S., Teixeira, A., Rama, L., Swancott, A., Hardy, L., Lee, B., . . . Thake, D. (2013b). Water and sodium intake habits and status of ultra-endurance runners during a multi-stage ultra-marathon conducted in a hot ambient environment: An observational study. *Nutrition Journal*, 12(13), 1–16.
- Cox, G.R., Clark, S.A., Cox, A.J., Halson, S.L., Hargreaves, M., Hawley, J.A., . . . Burke, L.M. (2010). Daily training with high carbohydrate availability increases exogenous carbohydrate oxidation during endurance cycling. *Journal of Applied Physiology*, 109(1), 126–134. PubMed ID: 20466803 doi:10.1152/jappphysiol.00950.2009
- Degache, F., Morin, J.B., Oehen, L., Guex, K., Giardini, G., Schena, F., . . . Millet, G.P. (2016). Running mechanics during the world’s most challenging mountain ultramarathon. *International Journal of Sports Physiology and Performance*, 11(5), 608–614. PubMed ID: 26457730 doi:10.1123/ijsp.2015-0238
- Deutsche Ultramarathon Vereinigung. (2018). *Ultra marathon statistics*. <http://statistik.d-u-v.org/index.php>
- Eden, B.D., & Abernethy, P.J. (1994). Nutritional intake during an ultraendurance running event. *International Journal of Sports Nutrition*, 4(2), 166–174. doi:10.1123/ijnsn.4.2.166
- Enqvist, J.K., Mattsson, C.M., Johansson, P.H., Brink-Elfegoun, T., Bakkman, L., & Ekblom, B.T. (2010). Energy turnover during 24 hours and 6 days of adventure racing. *Journal of Sports Science*, 28(9), 947–955. doi:10.1080/02640411003734069
- Epstein, Y., Roberts, W.O., Golan, R., Heled, Y., Sorkine, P., & Halpern, P. (2015). Sepsis, septic shock, and fatal exertional heat stroke. *Current Sports Medicine Reports*, 14(1), 64–69. PubMed ID: 25574888 doi:10.1249/JSR.0000000000000112
- Fornasiero, A., Savoldelli, A., Fruet, D., Boccia, G., Pellegrini, B., & Schena, F. (2018). Physiological intensity profile, exercise load and performance predictors of a 65-km mountain ultra-marathon. *Journal of Sports Science*, 36(11), 1287–1295. doi:10.1080/02640414.2017.1374707
- Gaskell, S.K., Snipe, R.M.J., & Costa, R.J.S. (2018a). Test-Retest Reliability of a Modified Visual Analog Scale Assessment Tool for Determining Incidence and Severity of Gastrointestinal Symptoms

- in Response to Exercise Stress.. *International Journal of Sport Nutrition and Exercise Metabolism*, 1–9. PubMed ID: 30632417 doi:10.1123/ijnsnem.2018-0215
- Gill, S.K., Teixeira, A., Rama, L., Rosado, F., Hankey, J., Scheer, V., . . . Costa, R.J.S. (2015). Circulatory endotoxin concentration and cytokine profile in response to exertional-heat stress during a multi-stage ultra-marathon competition. *Exercise Immunology Review*, 21, 114–128. PubMed ID: 25830597
- Gucciardi, D.F., Hanton, S., Gordon, S., Mallett, C.J., & Temby, P. (2015). The concept of mental toughness: Tests of dimensionality, nomological network, and traitness. *Journal of Personality*, 83(1), 26–44. PubMed ID: 24428736 doi:10.1111/jopy.12079
- Heaney, S., O'Connor, H., Michael, S., Gifford, J., & Naughton, G. (2011). Nutrition knowledge in athletes: A systematic review. *International Journal of Sport Nutrition and Exercise Metabolism*, 21(3), 248–261. PubMed ID: 21719906 doi:10.1123/ijnsnem.21.3.248
- Hew-Butler, T., Rosner, M.H., Fowkes-Godek, S., Dugas, J.P., Hoffman, M.D., Lewis, D.P., . . . Verbalis, J.G. (2015). Statement of the 3rd international exercise-associated hyponatremia consensus development conference, Carlsbad, California, 2015. *Clinical Journal of Sport Medicine*, 25(4), 303–320. PubMed ID: 26102445 doi:10.1097/JSM.0000000000000221
- Hoffman, M.D. (2014). Pacing by winners of a 161-km mountain ultramarathon. *International Journal of Sports Physiology and Performance*, 9(6), 1054–1056. PubMed ID: 24664982 doi:10.1123/ijsp.2013-0556
- Hoffman, M.D., Cotter, J.D., Goulet, É.D., & Laursen, P.B. (2016). VIEW: Is drinking to thirst adequate to appropriately maintain hydration status during prolonged endurance exercise? Yes. *Wilderness and Environmental Medicine*, 27(2), 192–195. PubMed ID: 27291699 doi:10.1016/j.wem.2016.03.003
- Hoffman, M.D., & Fogard, K. (2011). Factors related to successful completion of a 161-km ultramarathon. *International Journal of Sports Physiology and Performance*, 6(1), 25–37. PubMed ID: 21487147 doi:10.1123/ijsp.6.1.25
- Hoffman, M.D., Goulet, E.D.B., & Maughan, R.J. (2018a). Considerations in the use of body mass change to estimate change in hydration status during a 161-kilometer ultramarathon running competition. *Sports Medicine*, 48(2), 243–250. doi:10.1007/s40279-017-0782-3
- Hoffman, M.D., Ong, J.C., & Wang, G. (2010). Historical analysis of participation in 161 km ultramarathons in North America. *International Journal of History in Sport*, 27(11), 1877–1891. doi:10.1080/09523367.2010.494385
- Hoffman, M.D., Pasternak, A., Rogers, I.R., Khodae, M., Hill, J.C., Townes, D.A., . . . Lipman, G.S. (2014). Medical services at ultra-endurance foot races in remote environments: medical issues and consensus guidelines. *Sports Medicine*, 44(8), 1055–1069. PubMed ID: 24748459 doi:10.14814/phy2.12803
- Hoffman, M.D., Snipe, R.M.J., & Costa, R.J.S. (2018b). Ad libitum drinking adequately supports hydration during 2 h of running in different ambient temperatures. *European Journal of Applied Physiology*, 118(12), 2687–2697. doi:10.1007/s00421-018-3996-7
- Hoffman, M.D., & Stuempfle, K.J. (2014). Hydration strategies, weight change and performance in a 161 km ultramarathon. *Research in Sports Medicine*, 22, 213–225. PubMed ID: 24950110 doi:10.1080/15438627.2014.915838
- Hoffman, M.D., & Stuempfle, K.J. (2015). Sodium supplementation and exercise-associated hyponatremia during prolonged exercise. *Medicine and Science in Sports and Exercise*, 47(9), 1781–1787. PubMed ID: 25551404 doi:10.1249/MSS.0000000000000599
- Hoffman, M.D., & Stuempfle, K.J. (2016). Is sodium supplementation necessary to avoid dehydration during prolonged exercise in the heat? *Journal of Strength and Conditioning Research*, 30(3), 615–620. PubMed ID: 26907835 doi:10.1519/JSC.0000000000001138
- Hoffman, M.D., Stuempfle, K.J., & Valentino, T. (2015). Sodium intake during an ultramarathon does not prevent muscle cramping, dehydration, hyponatremia, or nausea. *Sport Medicine Open*, 1(1), 39. doi:10.1186/s40798-015-0040-x
- Horner, K.M., Schubert, M.M., Desbrow, B., Byrne, N.M., & King, N.A. (2015). Acute exercise and gastric emptying: A meta-analysis and implication for appetite control. *Sports Medicine*, 45(5), 659–678. PubMed ID: 25398225 doi:10.1007/s40279-014-0285-4
- Howe, C.C., Alshehri, A., Muggeridge, D., Mullen, A.B., Boyd, M., Spendiff, O., & Watson, D.G. (2018). Untargeted metabolomics profiling of an 80.5 km simulated treadmill ultramarathon. *Metabolites*, 8(1), 14. doi:10.3390/metabo8010014
- Impey, S.G., Hammond, K.M., Shepherd, S.O., Sharples, A.P., Stewart, C., Limb, M., . . . Morton, J.P. (2016). Fuel for the work required: A practical approach to amalgamating train-low paradigms for endurance athletes. *Physiology Reports*, 4(10), e12803. doi:10.14814/phy2.12803
- Jeukendrup, A. (2014). A step towards personalized sports nutrition: Carbohydrate intake during exercise. *Sports Medicine*, 44(Suppl. 1), 25–33. doi:10.1007/s40279-014-0148-z
- Kato, H., Suzuki, K., Bannai, M., & Moore, D.R. (2016). Protein requirements are elevated in endurance athletes after exercise as determined by the indicator amino acid oxidation method. *PLoS ONE*, 11(6), e0157406. PubMed ID: 27322029 doi:10.1371/journal.pone.0157406
- Kerhervé, H.A., Millet, G.Y., & Solomon, C. (2015). The dynamics of speed selection and psycho-physiological load during a mountain ultramarathon. *PLoS ONE*, 10(12), e0145482. doi:10.1371/journal.pone.0145482
- Koopman, R., Pannemans, D.L., Jeukendrup, A.E., Gijzen, A.P., Senden, J.M., Halliday, D., . . . Wagenmakers, A.J. (2004). Combined ingestion of protein and carbohydrate improves protein balance during ultra-endurance exercise. *American Journal of Physiology-Endocrinology and Metabolism*, 287(4), E712–E720. PubMed ID: 15165999 doi:10.1152/ajpendo.00543.2003
- Kruseman, M., Bucher, S., Bovard, M., Kayser, B., & Bovier, P.A. (2005). Nutrient intake and performance during a mountain marathon: An observational study. *European Journal of Applied Physiology*, 94(1–2), 151–157. doi:10.1007/s00421-004-1234-y
- Leiper, J.B. (2015). Fate of ingested fluids: Factors affecting gastric emptying and intestinal absorption of beverages in humans. *Nutrition Reviews*, 73(S2), 57–72. doi:10.1093/nutrit/nuv032
- Lewis, N.A., Collins, D., Pedlar, C.R., & Rogers, J.P. (2015). Can clinicians and scientists explain and prevent unexplained under-performance syndrome in elite athletes: An interdisciplinary perspective and 2016 update. *BMJ Open Sport and Exercise Medicine*, 1(1), e000063. PubMed ID: 27900140 doi:10.1136/bmjsem-2015-000063
- Lis, D.M., Kings, D., & Larson-Meyer, D.E. (2019). Dietary practices adopted by track-and-field athletes: Gluten-free, low FODMAP, vegetarian, and fasting. *International Journal of Sport Nutrition and Exercise Metabolism*, 29. doi:10.1123/ijnsnem.2018-0309
- Martin, T., Arnal, P.J., Hoffman, M.D., & Millet, G.Y. (2018). Sleep habits and strategies of ultramarathon runners. *PLoS ONE*, 13(5), e0194705. PubMed ID: 29742118 doi:10.1371/journal.pone.0194705
- Martinez, S., Aguilo, A., Rodas, L., Lozano, L., Moreno, C., & Tauler, P. (2018). Energy, macronutrient and water intake during a mountain ultramarathon event: The influence of distance. *Journal of Sports Science*, 36(3), 333–339. doi:10.1080/02640414.2017.1306092
- Maughan, R.J., Shirreffs, S.M., & Leiper, J.B. (2007). Errors in the estimation of hydration status from changes in body mass. *Journal*

- of Sports Sciences, 25, 797–804. PubMed ID: 17454547 doi:10.1080/02640410600875143
- McCubbin, A.J., & Costa, R.J.S. (2018). Impact of sodium ingestion during exercise on endurance performance: A systematic review. *International Journal of Sports Science*, 8(3), 97–107.
- McCubbin, A.J., Cox, G.R., & Broad, E.M. (2016). Case study: Nutrition planning and intake for marathon des sables—a series of five runners. *International Journal of Sports Nutrition and Exercise Metabolism*, 26(6), 581–587. doi:10.1123/ijnsnem.2016-0016
- McCubbin, A.J., Cox, G.R., & Costa, R.J.S., (2018). Sodium intake beliefs, information sources, and intended practices of endurance athletes before and during exercise. *International Journal of Sports Nutrition and Exercise Metabolism*. PubMed ID: 30507276 doi:10.1123/ijnsnem.2018-0270
- McDermott, B.P., Anderson, S.A., Armstrong, L.E., Casa, D.J., Cheuvront, S.N., Cooper, L., . . . Roberts, W.O. (2017). National Athletic Trainers' Association position statement: Fluid replacement for the physically active. *Journal of Athletic Training*, 52(9), 877–895. PubMed ID: 28985128 doi:10.4085/1062-6050-52.9.02
- Mountjoy, M., Sundgot-Borgen, J.K., Burke, L.M., Ackerman, K.E., Blauwet, C., Constantini, N., . . . Budgett, R. (2018). IOC consensus statement on relative energy deficiency in sport (RED-S): 2018 update. *British Journal of Sports Medicine*, 52(11), 687–697. PubMed ID: 29773536 doi:10.1136/bjsports-2018-099193
- Nikolaidis, P.T., & Knechtle, B. (2017). Physiology and pathophysiology in ultra-marathon running. *Frontiers in Physiology*, 9, 634.
- Oliver, S.J., Costa, R.J.S., Laing, S.J., Bilzon, J.L.J., & Walsh, N.P. (2009). One night of sleep deprivation decreases treadmill endurance performance. *European Journal of Applied Physiology*, 107(2), 155–161. PubMed ID: 19543909 doi:10.1007/s00421-009-1103-9
- Pinckaers, P.J., Churchward-Venne, T.A., Bailey, D., van Loon, L.J. (2017). Ketone bodies and exercise performance: The next magic bullet or merely hype? *Sports Medicine*, 47(3), 383–391. PubMed ID: 27430501 doi:10.1007/s40279-016-0577-y
- Phillips, S.M., & Van Loon, L.J. (2011). Dietary protein for athletes: From requirements to optimum adaptation. *Journal of Sports Science*, 29(Suppl. 1), S29–S38. doi:10.1080/02640414.2011.619204
- Rauch, C.E., Khoo, A.Y., Miall, A., Snipe, R.M.J., & Costa, R.J.S. (2018). Non-protein oxidation rates of ultramarathon runners in response to incremental intensity and prolonged strenuous running. *International Journal of Sports Physiology and Performance*, 38(S1):8.
- Sawka, M.N., Montain, S.J., & Latzka, W.A. (2001). Hydration effects on thermoregulation and performance in the heat. *Comparative Biochemistry and Physiology. Part A, Molecular & Integrative Physiology*, 128(4), 679–690. PubMed ID: 11282312 doi:10.1016/S1095-6433(01)00274-4
- Schütz, U.H., Billich, C., König, K., Würslin, C., Wiedelbach, H., Brambs, H.J., & Machann, J. (2013). Characteristics, changes and influence of body composition during a 4486 km transcontinental ultramarathon: Results from the TransEurope FootRace mobile whole body MRI-project. *BMC Medicine*, 11, 122. doi:10.1186/1741-7015-11-122
- Schwellnus, M., Soligard, T., Alonso, J.M., Bahr, R., Clarsen, B., Dijkstra, H.P., . . . Engebretsen, L. (2016). How much is too much? (Part 2) International Olympic Committee consensus statement on load in sport and risk of illness. *British Journal of Sports Medicine*, 50(17), 1043–1052. PubMed ID: 27535991 doi:10.1136/bjsports-2016-096572
- Smith, J., Pascoe, D.D., Passe, D.H., Ruby, B.C., Stewart, L.K., Baker, L.B., & Zachwieja, J.J. (2013). Curvilinear dose-response relationship of carbohydrate (0–120 g·h⁻¹) and performance. *Medicine & Science in Sports & Exercise*, 45(2), 336–341. doi:10.1249/MSS.0b013e31827205d1
- Snipe, R.M.J., Khoo, A., Kitic, C., Gibson, P., & Costa, R.J.S. (2018). Heat stress during prolonged running results in exacerbated intestinal epithelial injury and gastrointestinal symptoms. *European Journal of Applied Physiology*, 118(2), 389–400. PubMed ID: 29234915 doi:10.1007/s00421-017-3781-z
- Soligard, T., Schwellnus, M., Alonso, J.M., Bahr, R., Clarsen, B., Dijkstra, H.P., . . . Engebretsen, L. (2016). How much is too much? (Part 1) International Olympic Committee consensus statement on load in sport and risk of injury. *British Journal of Sports Medicine*, 50(17), 1030–1041. PubMed ID: 27535989 doi:10.1136/bjsports-2016-096581
- Stellingwerff, T. (2016). Competition nutrition practices of elite ultramarathon runners. *International Journal of Sport Nutrition and Exercise Metabolism*, 26(1), 93–99. PubMed ID: 26061831 doi:10.1123/ijnsnem.2015-0030
- Stellingwerff, T., & Cox, G.R. (2014). Systematic review: Carbohydrate supplementation on exercise performance or capacity of varying durations. *Applied Physiology Nutrition and Metabolism*, 39(9), 998–1011. doi:10.1139/apnm-2014-0027
- Stevens, C.J., Taylor, L., & Dascombe, B.J. (2017). Cooling during exercise: An overlooked strategy for enhancing endurance performance in the heat. *Sports Medicine*, 47(5), 829–841. PubMed ID: 27670904 doi:10.1007/s40279-016-0625-7
- Stuempfle, K.J., Hoffman, M.D., Weschler, L.B., Rogers, I.R., & Hew-Butler, T. (2011). Race diet of finishers and non-finishers in a 100 mile (161 km) mountain footrace. *Journal of the American College of Nutrition*, 30(6), 529–535. PubMed ID: 22331688 doi:10.1080/07315724.2011.10719999
- Tam, N., Nolte, H.W., & Noakes, T.D. (2011). Changes in total body water content during running races of 21.1 km and 56 km in athletes drinking ad libitum. *Clinical Journal of Sport Medicine*, 21, 218–225. PubMed ID: 21427566 doi:10.1097/JSM.0b013e31820eb8d7
- Tarnopolsky, M.A., MacDougall, J.D., & Atkinson, S.A. (1988). Influence of protein intake and training status on nitrogen balance and lean body mass. *Journal of Applied Physiology*, 64(1), 187–193. PubMed ID: 3356636 doi:10.1152/jappl.1988.64.1.187
- Thomas, D.T., Erdman, K.A., & Burke, L.M. (2016). American College of Sports Medicine joint position statement. Nutrition and athletic performance. *Medicine & Science in Sports & Exercise*, 48(3), 543–568. doi:10.1249/MSS.0000000000000852
- Vernillo, G., Giandolini, M., Edwards, W.B., Morin, J.B., Samozino, P., Horvais, N., & Millet, G.Y. (2017). Biomechanics and physiology of uphill and downhill running. *Sports Medicine*, 47(4), 615–629. PubMed ID: 27501719 doi:10.1007/s40279-016-0605-y
- Volek, J.S., Freidenreich, D.J., Saenz, C., Kunces, L.J., Creighton, B.C., Bartley, J.M., . . . Phinney, S.D. (2016). Metabolic characteristics of keto-adapted ultra-endurance runners. *Metabolism: Clinical and Experimental*, 65(3), 100–110. doi:10.1016/j.metabol.2015.10.028
- Wall, B.A., Watson, G., Peiffer, J.J., Abbiss, C.R., Siegel, R., & Laursen, P.B. (2015). Current hydration guidelines are erroneous: Dehydration does not impair exercise performance in the heat. *British Journal of Sports Medicine*, 49(16), 1077–1083. PubMed ID: 24055782 doi:10.1136/bjsports-2013-092417
- Williamson, E. (2016). Nutritional implications for ultra-endurance walking and running events. *Extreme Physiology and Medicine*, 5, 13. PubMed ID: 27895900 doi:10.1186/s13728-016-0054-0