

UCI Sports Nutrition Project: Considerations and Applications for the Use of Sports Foods and Supplements to Improve Performance in Cycling

Jamie Whitfield,¹ Brendan Egan,^{2,3} Juan Del Coso,⁴ Wim Derave,⁵
Bryan Saunders,^{6,7,8} and Louise M. Burke¹

¹Centre for Human Metabolism and Performance, Mary MacKillop Institute for Health Research, Australian Catholic University, Melbourne, VIC, Australia; ²School of Health and Human Performance, Dublin City University, Dublin, Ireland; ³Florida Institute for Human and Machine Cognition, Pensacola, FL, USA; ⁴Sport Sciences Research Centre, Rey Juan Carlos University, Fuenlabrada, Spain; ⁵Department of Movement and Sports Sciences, Ghent University, Ghent, Belgium; ⁶Applied Physiology and Nutrition Research Group, School of Physical Education and Sport and Faculdade de Medicina FMUSP, Universidade de São Paulo, São Paulo, SP, Brazil; ⁷Center of Lifestyle Medicine, Faculdade de Medicina FMUSP, Universidade de São Paulo, São Paulo, SP, Brazil; ⁸Nutrology Academy, Rio de Janeiro, RJ, Brazil

The use of sports foods and supplements has become ubiquitous among cyclists of all disciplines in order to meet energy and nutrient targets and to improve performance and recovery outcomes. This review will provide an overview of the different types of products and the rationale for their use, while highlighting key considerations surrounding the safety and anti-doping risks that supplements pose among athletes. A summary of supplements with a strong evidence base (caffeine, creatine, sodium bicarbonate, beta-alanine, dietary nitrate, and glycerol) and emerging supplements popularized within cycling (exogenous ketones) is also provided, outlining accepted protocols for use, timing, and potential ergogenic effects or side effects.

Keywords: caffeine, creatine, nutritional buffers, nitrate, ketones

The sport of cycling is composed of multiple disciplines (e.g., road, mountain biking, track, BMX, and gravel), many of which can be further subcategorized into individual events, each with unique physiological demands induced by the intensity, duration, and environment in which it takes place. Although these variations make “one-size fits-all” nutrition recommendations for cyclists impossible, the use of sports foods and supplements has become commonplace within the sports nutrition plans and practices of cyclists across all disciplines. Indeed, reviews have identified that age, biological sex, athlete caliber, and sport discipline all influence supplement use (Burke & Slater, 2021; Garthe & Maughan, 2018; Thomas et al., 2016), and surveys of high-performance (i.e., national level or higher, Tier 3+; McKay et al., 2022) cyclists have consistently reported a high prevalence of supplement use, ranging from 85% to 100% among participants (Baltazar-Martins et al., 2019; Huang et al., 2006; Loraschi et al., 2014).

Although a “food first” approach focusing on nutrient-rich and less processed foods is a foundation of modern sports nutrition (Close et al., 2022), a range of factors in cycling create scenarios in which a “food-only” approach is not viable. In this regard, sports foods and supplements can uniquely assist cyclists to meet their specialized energy and nutrient targets or to improve health, performance, and recovery outcomes (Burke & Slater, 2021). This

review is part of series of articles commissioned by Union Cycliste Internationale (UCI) contributing to the preparation of a consensus statement on nutrition for cycling and will provide an overview of the different types of products most frequently used in cycling and the rationale for their uses, as well as highlighting some caveats, considerations, and contemporary applications of sports foods and supplements. Although specific recommendations are difficult to make due to the range of outcomes and physiological determinants underpinning each cycling discipline, priority will be given to supplements with the best evidence of adding value to cyclists’ nutrition plans, as well as those that are highly publicized within the sport. Where sufficient detail has been provided, participants from referenced literature will be classified according to performance caliber as either Tier 1 (recreationally active, participating in multiple sports), Tier 2 (trained/developmental, local level athlete training ~3 times per week with an intent to compete), Tier 3 (highly trained/national level athletes), Tier 4 (elite athletes competing at the international level), or Tier 5 (world class, Olympic and/or World Championship medalists) according to a recently published framework (McKay et al., 2022).

A Working Definition of Sports Foods and Supplements

The term “sports foods” generally refers to specific products designed for use by athletes either in preparation for, during, or following competition and/or training (Burke & Slater, 2021). Broadly speaking, these foods focus on the provision of macronutrients including carbohydrate and protein and are often prepackaged to combine the desired quantities required within a single source that is easy to prepare, transport, and/or consume in sport-specific environments. By contrast, dietary supplements can refer to any food, food component, or compound that is ingested in addition to an

Egan <https://orcid.org/0000-0001-8327-9016>

Del Coso <https://orcid.org/0000-0002-5785-984X>

Derave <https://orcid.org/0000-0002-2225-5587>

Saunders <https://orcid.org/0000-0003-0995-9077>

Burke <https://orcid.org/0000-0001-8866-5637>

Whitfield (jamie.whitfield@acu.edu.au) is corresponding author, <https://orcid.org/0000-0002-8961-8872>

Del Coso is now affiliated with the Institute of Health and Sport Sciences, Faculty of Health Sciences, Universidad Francisco de Vitoria, Madrid, Spain.

individual's habitual diet in order to achieve a specific health and/or performance benefit (Maughan et al., 2018). Various groups have tried to provide tools to classify sports foods and supplements according to their function/mechanism of action, the strength of evidence for their use, and the risk of detrimental outcomes. The most recognized schemes include the Sports Supplement Framework of the Australian Institute of Sport (The AIS Sports Supplement Framework, 2025) and the Position Stand of the International Olympic Committee on Dietary Supplements and the High-Performance Athlete (Maughan et al., 2018). Table 1 summarizes the common presentation and evidence-based uses of various products that fit the categories of sports foods (e.g., bespoke products which can be used by cyclists across all disciplines to meet their energy and nutrient needs when it is impractical to use everyday foods) or medical supplements (formulations which can be used under the supervision of a sports physician or dietitian to prevent or treat micronutrient deficiencies). Such products contribute to the nutrition plans of many cyclists, particularly in scenarios of elevated requirements or challenges to food availability or intake.

Specific Supplements With an Evidence Base or Topical Interest for Use in Cycling

Whole foods and sport foods are the primary method for supporting fueling and training; however, a wide range of supplements are available in individual or combined formulations that make claims of directly or indirectly improving athletic performance. These products are a frequent topic of discussion among riders and coaches, often targeting race scenarios in which they might provide a small but worthwhile improvement in performance. However, despite the multitude of supplements purporting to specifically target performance outcomes in athletes, very few are supported by robust scientific evidence. For example, the only performance supplements classified as Group A (those with a sound evidence base) by the AIS Sports Supplement Framework (2025) are caffeine, creatine, beta-alanine (BA), sodium bicarbonate, dietary nitrate, and glycerol. Therefore, this review will investigate the potential applications of these specific supplements with the strongest evidence base within cycling. In addition, we will highlight the current evidence for exogenous ketone supplements (considered to be a Group B supplement—evolving evidence; The AIS Sports Supplement Framework, 2025) due to their history of use and topical interest within cycling. Although not discussed in the context of each individual supplement, we note that much of the research performed to date has been performed in recreationally active/lower competitive tier male athletes (e.g., Tier 2–3). Indeed, in a recent audit of the literature on evidence-based performance supplements found across 1,826 studies with 34,889 participants, just 23% of participants were women, and only 9% ($n = 778$) of men and 19% ($n = 323$) of women were classified as elite (Tier 4 or 5; Smith, McKay, Ackerman, et al., 2022). Recent work has highlighted the physiological differences between elite and recreationally active athletes in other disciplines and the ensuing ramifications on the exercise intensity/duration relationship (Burke et al., 2025). Further work is therefore required in some instances to determine the efficacy of these supplements across the range of UCI recognized disciplines.

Caffeine

Caffeine is a well-known psychoactive substance with stimulatory effects, most commonly consumed via coffee and other foods and

beverages including green tea, cocoa, chocolate, and yerba mate derivatives such as chimarrão (Rocha et al., 2022). There are several mechanisms via which caffeine may improve cycling performance of varying distances and intensities. Some studies have demonstrated increased oxidation of fat (Conger et al., 2023) and exogenous carbohydrate (Yeo et al., 2005) during exercise, thereby potentially sparing endogenous glycogen; however, this finding is not universal (Graham et al., 2008). Caffeine may also increase sarcoplasmic reticulum calcium release, but its most well-recognized effect occurs via antagonism of the adenosine receptors in the central nervous system (Nehlig et al., 1992) to increase focus and pacing via a reduction in fatigue and perception of effort. Alternatively, performance improvements from caffeine intake may occur and/or be enhanced via placebo effects (Beedie et al., 2006; Saunders, de Oliveira, et al., 2017). There is also data to suggest that caffeine may enhance postexercise glycogen resynthesis (Loureiro et al., 2021; Pedersen et al., 2008).

Caffeine has been shown to be an effective performance-enhancing supplement across a range of cycling time-trial distances and durations, including 30 s (4% increase in peak power output) (Grgic, 2018), 1 km (3% faster) (Wiles et al., 2006), 4 km (~2% faster) (Felippe et al., 2018; Tomazini et al., 2020), 10 km (2% faster) (Graham-Paulson et al., 2016), ~30 min (4% increase in mean power output) (Saunders, de Oliveira, et al., 2017), 1 hr (5% greater distance covered) (McNaughton, Lovell, et al., 2008), and 40 km (3.5% increase in mean power output) (Foad et al., 2008). Collectively, these findings suggest that caffeine can be utilized to improve performance across most, if not all, cycling disciplines.

The current recommendations for dosing and timing suggest that 3–6 mg/kg body mass (BM) (Guest et al., 2021) leads to performance improvements, with timing varying depending on form of administration (see Table 2). However, for prolonged cycling events lasting several hours (i.e., road, gravel, or mountain bike events ≥ 2 hr), supplementing prior to exercise may not always be optimal because the half-life of caffeine is only a few hours (Grzegorzewski et al., 2021) and its peak efficacy may be within the initial period postsupplementation early in the event (Bell & McLellan, 2002; Harty et al., 2020). Thus, periodic supplementation throughout exercise may be more efficient during prolonged endurance exercise, specifically targeting moments when increased performance may be necessary, such as an intermediate sprint or climb during road cycling, or when there is increased fatigue, such as toward the end of a race. Caffeine ingestion late in exercise, via the form of Coca-Cola (Cox et al., 2002) or 100 or 200 mg provided in capsules (Talanian & Spriet, 2016), has been shown to increase subsequent cycling time-trial performance by 3.5% and 4%–7%, respectively. Interestingly, ingesting a staggered dose of caffeine (6×1 mg/kg BM every 20 min) throughout 2 hr endurance exercise was equally effective as ingesting the same total dose as a single bolus 1 hr preexercise (~3% improvement in time to complete a 7 kJ/kg BM time trial following a 2-hr preload at 70% $\dot{V}O_{2\text{peak}}$) (Cox et al., 2002). Such staggered strategies might be considered particularly useful during prolonged endurance events or during ultraendurance events, for which caffeine's effects are desired over several hours.

The most traditional form of caffeine administration is providing anhydrous caffeine in capsule form though some athletes may prefer to ingest caffeine via alternative sources including energy drinks and gels or chewing gum. However, there has been limited work exploring the impact of gels on cycling-specific performance, and work employing energy drinks is often confounded by other ingredients including carbohydrate (Wickham &

Table 1 Working Classifications of Sports Foods and Supplements

Category	Examples	Typical forms	Typical composition/ characteristics	Uses during cycling
Sports foods	Sports drink—common	Powder or liquid (ready to drink)	• 5%–8% CHO • 10–25 mmol/L sodium	Contribute to fuel and rehydration plans during training sessions and races
	Sports drinks—specialized		• Higher CHO concentrations (e.g., up to ~15% CHO) • May have glucose:fructose blends proposed to promote greater rates of gut absorption • May involve hydrogel technology (pectin + alginate gel agents) proposed to promote great rates of stomach emptying • Higher sodium concentrations (e.g., 30–50 mmol/L) • May contain caffeine	Designed to enhance gut uptake and tolerance, allowing greater rates of CHO delivery to muscle and support aggressive in-race fueling goals Designed to increase sodium replacement during lengthy races or in riders with high sweat rates/higher sweat sodium concentrations
	Sports gel	30–40 g sachets	• 60%–70% CHO (25–40 g CHO per sachet) • Many contain glucose:fructose blends (see sports drinks) • May involve hydrogel technology (see sports drinks) • May contain caffeine or electrolytes	Contribute to fuel plans (and caffeine use) during training sessions and races Contribute to prerace fuel plans See notes for specialized sports drinks regarding enhanced gut handling characteristics
	Sports confectionary	Jelly-type confectionary (generally 5–6 g each in pouch of ~40–50 g)	• 90% CHO confectionery items (~5 g per piece) • Many contain glucose:fructose blends (see sports drinks) • May involve hydrogel technology (see sports drinks) • May contain caffeine or electrolytes	Contribute to fuel plans (and caffeine use) during training sessions and races Contribute to prerace fuel plans See notes for specialized sports drinks regarding gut enhancement characteristics
	Sports bars	40–60 g bars CHO focused	• 40–50 g CHO • 5–10 g protein • Usually low in fat and fiber • May contain 50%–100% of DRIs key vitamins/minerals • May contain amino acids	Contribute to fuel plans during training sessions and races Contribute to prerace and postrace fuel plans, especially when compact and low-fiber choices are useful
		40–60 g bar Protein focused	• 20–40 g protein • 5–10 g CHO • Usually low in fat • 50%–100% of DRIs key vitamins/minerals • May contain amino acids, creatine, or other performance/recovery aids	Contribute to protein intake goals, especially post-training/races or high energy phases (e.g., intensified training, muscle gain phase) especially when compact choices are useful
	Protein supplements	Powder (mix with water or milk) or ready to drink	• Powder of 70%–90% protein content from whey or other animal/vegetable protein sources (e.g., milk, pea, soy) • May have other ingredients: amino acids, creatine, and other performance aids	Contribute to protein intake goals, especially post-training/races or high energy phases (e.g., intensified training, muscle gain phase) especially when compact and low-fiber choices are useful
	Liquid meal supplement	Powder (mix with water or milk) or ready to drink	• 1–1.5 kcal/ml • 15%–20% protein • 50%–70% CHO • Low to moderate fat • May contain 50%–100% of DRIs key vitamins/minerals	Contribute to energy and nutrient goals, especially posttraining/races or high energy phases (e.g., intensified training, muscle gain phase) especially when low fiber/quickly digested choices are valuable Prerace meal when low fiber/quickly digested choices are valuable

(continued)

Table 1 (continued)

Category	Examples	Typical forms	Typical composition/ characteristics	Uses during cycling
Vitamins and minerals	Electrolyte supplement	Powder, tablets, or ready to drink	0%–2% CHO 50–60 mmol/L sodium 10–20 mmol/L potassium	Replace large sodium losses during lengthy races/ training sessions Rapid and effective rehydration following moderate-large fluid and sodium deficits in races or training sessions
	Calcium	Capsule/tablet	Calcium carbonate/phosphate/lactate	Supplement calcium in low-energy or low dairy food diet Prevent/treat osteopenia/osteoporosis in cyclists at risk (under supervision)
	Iron	Capsule/tablet	Ferrous sulfate/gluconate/fumarate	Prevent/treat iron deficiency in cyclists at risk (under supervision) Optimize iron status before/during altitude training
	Vitamin D	Capsule/tablet	Vitamin D3	Prevent/treat vitamin D deficiency in cyclists at risk (under supervision)

Note. CHO = carbohydrate; DRI = daily recommended intakes. Adapted from “IOC Consensus Statement: Dietary Supplements and the High-Performance Athlete,” by R.J. Maughan, L.M. Burke, J. Dvorak, D.E. Larson-Meyer, P. Peeling, S.M. Phillips, E.S. Rawson, N.P. Walsh, I. Garthe, H. Geyer, R. Meeusen, L.J.C. van Loon, S.M. Shirreffs, L.L. Spriet, M. Stuart, A. Vernece, K. Currell, V.M. Ali, R.G. Budgett, . . . L. Engebretsen, 2018, *British Journal of Sports Medicine*, 52(7), pp. 439–455. Copyright 2018 BMJ Publishing Group Ltd & British Association of Sport and Exercise Medicine and “The AIS Sports Supplement Framework,” by The AIS Sports Supplement Framework, 2025. <https://www.ais.gov.au/nutrition/supplements>. Copyright 2025 by Australian Sports Commission.

Table 2 Summary of Supplements Used to Improve Cycling Performance

Supplement	Dose and form	Timing	Half life or washout	Possible side effects
Group A: Strong evidence base				
Beta-alanine	4–6 g/day Form: Slow-release tablets recommended	4+ weeks	2% decrease per week (Stellingwerff et al., 2012), returning to baseline after several months	Paresthesia (i.e., tingling or pins and needles)
Caffeine	3–6 mg/kg BM Form: Drinks, tablets and/or gum	1 hr prior to exercise, or staggered doses for prolonged (i.e., multiple hours) endurance cycling gum may be utilized closer (i.e., 15 min prior) to exercise	Half-life: ~4–5 hr (range 2–12 hr) (Reddy et al., 2024)	Headache, agitation, jitteriness, anxiety, irritability, increased blood pressure, tachycardia and heart palpitations, insomnia and reduced sleep quality
Creatine	Rapid loading: 20 g/day for 7 days Prolonged loading: 3 g/day for 28 days Form: Powder	Daily doses	~30 days to return to baseline levels (~2.5–3 g/day decrease) (Hultman et al., 1996; Persky et al., 2003)	Weight gain via water retention
Dietary inorganic nitrate	Acute: 8–16 mmol Chronic: 4–16 mmol/day (Shannon et al., 2022) Form: Liquid (e.g., beetroot juice)	1.5–2 hr prior to exercise	Half-life: ~5–6 hr (Lundberg et al., 2008) in plasma	
Glycerol	1.0–1.5 g/kg BM in combination with 15–30 mL/kg BM water Form: Liquid	1–1.5 hr prior to exercise		Weight gain via water retention, bloating, nausea, and headaches
Sodium bicarbonate	0.3 g/kg BM Form: Enteric-coated capsules, hydrogel mixtures	1–3 hr prior to exercise	Varies between individuals, likely back to baseline within 24 hr postingestion	Gastrointestinal discomfort, potential risk associated with high sodium intakes
Group B: Requires further interrogation				
Ketone supplements	Optimal dose currently unknown, typically given as 286–573 mg/kg BM doses	1–2 hr prior to exercise or postexercise	Half-life: ~1–3 hr for β HB, 8–14 hr for AcAc (Clarke et al., 2012)	Gastrointestinal discomfort, dizziness, and hypoglycemia
Sodium citrate	Buffering: 0.5 g/kg BM Hyperhydration: 2–4 g combined with 15–30 mL/kg BM fluid	1–3 hr prior to exercise	Varies between individuals	Gastrointestinal discomfort, potential risk associated with high sodium intakes

Note. β -HB = β -hydroxybutyrate; AcAc = acetoacetate; BM = body mass.

Spriet, 2018). By contrast, chewing gum has shown promise as it is absorbed faster via the buccal mucosa compared with capsule intake and gut absorption (Kamimori et al., 2002) and has been shown to improve both fixed distance (~30–44 km; Lane et al., 2014; Paton et al., 2015) and fixed energy expenditure (7 kJ/kg; Ryan et al., 2013) cycling time-trial performance by 3%–5%. Preexercise coffee ingestion also remains popular among athletes, but the caffeine content of coffee has been shown to be highly variable (McCusker et al., 2003) making it difficult to ensure that the recommended dose is actually attained. Currently, data do not overly support the need to genotype for caffeine metabolism or sensitivity because these factors appear to have minimal contribution to the performance-enhancing effects of caffeine (Barreto et al., 2024; Carswell et al., 2020; Glaister et al., 2021; Muñoz et al., 2020), and curbing habitual caffeine consumption in the days prior to a race also appears unnecessary to optimize benefits (Carvalho et al., 2022). Some consideration of potential undesirable side effects is warranted; these can include headache, agitation, jitteriness, anxiety, irritability, increased blood pressure, tachycardia and heart palpitations, insomnia, and reduced sleep quality (Childs et al., 2008; de Souza et al., 2022; Guest et al., 2021). Cyclists who are prone to anxiety or competing in multiday events for which sleep disruptions need to be considered may wish to avoid caffeine in preliminary/qualifying rounds in favor of using it for key events/finals or maintain the lower end of recommended doses (i.e., ~3 mg/kg BM; Carvalho et al., 2022; Maughan et al., 2018) and ensure that doses > 100 mg are consumed at least 12 hr before bedtime (Gardiner et al., 2023, 2025) when subsequent sleep is a priority. Collectively, the current evidence suggests that caffeine is a well-supported, versatile ergogenic aid that can improve various aspects of cycling performance across distances and formats. However, its use should be individualized to optimize benefits while minimizing potential side effects, particularly subsequent sleep.

Creatine

The adenosine triphosphate (ATP)–phosphocreatine (PCr) system is the most rapidly available source of ATP supply for skeletal muscle metabolism (Hargreaves & Spriet, 2020). Within this pathway, PCr serves to provide an inorganic phosphate molecule for the rapid resynthesis of ATP and provides energy during moments of intense metabolic demand such as those during high-intensity exercise. The content of intramuscular creatine can be maximized through several days of oral creatine ingestion (i.e., 20 g/day for 7 days, Table 2; Harris et al., 1992), which may lead to improved performance, particularly during single and repeated-bout short-duration explosive and high-intensity efforts. There is solid evidence to support the efficacy of creatine for single and repeated cycling sprints. For example, ingesting 20 g of creatine per day for 5 days improved mean power output (+6%) during the first and second efforts of three maximal 30-s isokinetic cycle sprints separated by 4 min (Birch et al., 1994) and increased the total work done improved (+4%) during two 30-s maximal cycle sprints also separated by 4-min rest (Casey et al., 1996). Shorter duration repeated cycle sprints of 15 s may also be improved with creatine (provided as 0.3 g/kg BM), though these benefits were only apparent when sprint bouts were separated by intervals of 1 and 3, but not 6, min (Cottrell et al., 2002).

This capacity to improve sprint performance may also be relevant throughout prolonged cycling events (i.e., road, gravel, and cross-country and marathon mountain bike races) or in events

for which intermediate and final sprints are contested. Indeed, supplementation with 25 g/day for 5 days in elite cyclists improved both peak and mean power output in 5 × 10-s sprints following a ride to exhaustion at 4 mM lactate. Seven days of creatine supplementation with 20 g/day also increased the time to exhaustion during a graded exercise test (6%) and increased exercise intensity at ventilatory threshold, suggesting that creatine may also improve performance during longer aerobic efforts (Nelson et al., 2000). Creatine may also enhance muscle glycogen storage (Robinson et al., 1999) via an upregulation of the primary glucose transporter GLUT4 (Ju et al., 2005) and attenuate oxidative stress caused by exercise (Arazi et al., 2021), both of which may be of particular interest to cyclists engaged in multiday events that require substantial carbohydrate provision and/or have short recovery periods between stages. However, although creatine (20 g/day for 5 days) augmented glycogen stores by ~18% in recreationally active individuals (van Loon et al., 2004), other work failed to detect differences in preexercise glycogen in (Tier 2–3) cyclists supplementing with creatine or a placebo when also co-ingesting high amounts (6–12 g/kg BM) of carbohydrate (Tomcik et al., 2018).

A potential issue with creatine supplementation in cyclists who rely heavily on their power-to-weight ratio (i.e., Grand Tour general classification riders, climbing specialists, etc.) is the concerns surrounding increased weight gain via water retention. We note that, although some studies have reported as much as 2.5 kg BM increases in extreme cases (Balsom et al., 1993; Greenhaff et al., 1994), average increases are modest (0.5–1 kg) and likely limited to the initial few days of supplementation (Hall & Trojjan, 2013; Ziegenfuss et al., 1998). Furthermore, assessments of body composition in Tier 2–3 male cyclists via dual-energy X-ray absorptiometry following 5 days supplementing with 20 g of creatine per day and 2–9 days of a 3-g/day maintenance dose failed to show a significant increase in total or lean BM (~1.2% difference vs. baseline), reflecting a similar increase (1.3%) in total body water content assessed via bioelectrical impedance spectroscopy (Bone et al., 2017). Although these findings suggest that the risk of significant shifts in body composition/mass are likely overstated (Antonio et al., 2021), athletes and practitioners may wish to monitor BM changes with longer term supplementation. Although alternative forms exist, many have not been rigorously investigated; and therefore, creatine monohydrate remains the most effective form of creatine supplement for increasing muscle PCr stores and improving performance (Antonio et al., 2021). Overall, creatine supplementation appears to offer benefits to the performance of exercise that involves rapid generation of high power outputs, which are often key race-defining moments for several cycling disciplines including track cycling (Stanley et al., 2025 in review), BMX (Haakonssen et al., 2025 in review), road (Jeukendrup et al., 2025 in review), eSports and gravel (Whitfield et al., 2025 in review), and mountain biking (Oosthuysen et al., 2025 in review).

Sodium Bicarbonate and Sodium Citrate

Sodium bicarbonate and sodium citrate are two supplements that increase the bicarbonate concentration of the blood, which is considered a key component in mitigating the performance-limiting effects of acidosis that occurs during high-intensity exercise (McNaughton, Siegler, & Midgley, 2008). Buffering supplements such as these are often cited as being most effective during short-duration high-intensity exercise, but meta-analytical data suggest

that it can also be effective for longer duration activity (de Oliveira et al., 2022). Indeed, sodium bicarbonate has been shown to be effective across a range of cycling times and distances. Early work exploring the impact of 0.1–0.5 g/kg BM sodium bicarbonate doses showed significant increases (12%–19%) in peak power generated during a 60-s cycling ergometer test, with the highest improvement detected at a 0.3-g/kg BM dose (McNaughton, 1992a). Consequently, the minimum effective dose for sodium bicarbonate appears to be 0.2 g/kg BM, though 0.3 g/kg BM appears most effective (de Oliveira et al., 2022; McNaughton, 1992a) (Table 2). Work by the same authors using this dose also demonstrated improvements in peak power during 2- (9%) and 4-min (12%) cycling tests (McNaughton, 1992b). Time-trial (4-km) performance is also improved in trained cyclists (Tier 2) by ~2% following sodium bicarbonate ingestion (either 0.2 or 0.3 g/kg BM, with no differences detected between doses), as average power outputs were increased by ~6% compared with placebo (Gough et al., 2018). A 0.3-g/kg BM dose elicits similar performance improvements across 16-km (~2%) (Leach et al., 2023) and 40-km (1.4%) (Shannon et al., 2024) distances, and the total amount of work done in a 1-hr time trial was increased by ~14% (McNaughton, Dalton, & Palmer, 1999). Targeting supplementation to key periods in a race (e.g., final sprint) may also be effective as ingestion of 0.3 g/kg BM sodium bicarbonate as a split dose (150 mg/kg BM prior to exercise, followed by 50 mg·kg⁻¹ BM·hr⁻¹ during a 3-hr cycling bout that mimicked race demands), improved the average power output sustained during a final 90-s sprint by ~3% (Dalle et al., 2021). By contrast, work assessing real-world BMX performance in members of the Spanish National team with 15-min recovery failed to detect a difference in race performance (3×~30 s races with a 15-min recovery on an outdoor BMX track used for international competition) or peak velocity whether supplementing with 0.3 g/kg BM sodium bicarbonate or placebo (Peinado et al., 2019).

Although sodium citrate has received less attention as a buffering agent, ingestion of sodium citrate effectively raises blood bicarbonate concentrations (Urwin et al., 2019) with peak alkalosis occurring ~180–240 min postingestion (Urwin et al., 2021). Specifically, acute ingestion of 0.5 g/kg BM sodium citrate has been demonstrated to be most consistently ergogenic in untrained individuals for events lasting 60–240 s and very high intensity (>100% VO₂max) (Urwin et al., 2021). This includes short-duration cycling, as sodium citrate improved peak power output in untrained (Tier 1) individuals across 60 s (21%), 120 s (13%), and 240 s (9%) following the ingestion of a 0.5 g/kg BM dose (McNaughton, 1990; McNaughton & Cedaro, 1992). However, it may also improve longer duration exercise as the time to complete a 30-km time trial in Tier 2–3 cyclists was reduced by ~3% (Potteiger, Nickel, et al., 1996).

Ingestion of 0.3 or 0.5 g/kg BM of sodium bicarbonate or sodium citrate increases blood bicarbonate concentrations between 5 and 8 mmol (Urwin et al., 2023). Although peak alkalosis between the two supplements is similar (Potteiger, Webster, et al., 1996; Urwin et al., 2023), this peak occurs significantly later postingestion with sodium citrate (180–240 min) compared with sodium bicarbonate (120–180 min) (Urwin et al., 2023). The performance-enhancing effects of increased blood bicarbonate are apparent for a substantial time period, and athletes can expect to benefit from supplementation for at least between 1 and 4 hr postsupplementation (de Oliveira et al., 2020). To the best of our knowledge, no study has directly compared the two supplements at the recommended dosages to assess the ergogenic effects on

cycling-specific performance. However, a recent meta-analysis has suggested that sodium bicarbonate is more effective than sodium citrate for improving exercise performance (de Oliveira et al., 2022). Gastrointestinal discomfort associated with ingestion of buffers is commonly cited as a barrier to the use of this supplement during competition for athletes (Urwin et al., 2023); however, these symptoms can be decreased through the use of enteric (coated) capsules rather than solutions or via co-ingestion with carbohydrate (Carr et al., 2011). Athletes may also consider ingesting several smaller doses (e.g., 0.1 g/kg BM) staggered overall several hours; however, the results of a recent meta-analysis found that a single dose is more effective for enhancing exercise performance (de Oliveira et al., 2022). The development of novel formulations such as the “Maurten Bicarb System,” comprising sodium bicarbonate minitabets ingested alongside a carbohydrate hydrogel, have also been shown to reduce the severity of these side effects (Gough & Sparks, 2024) while maintaining the performance-enhancing capacity (Shannon et al., 2024).

In summary, sodium bicarbonate, and to a lesser extent sodium citrate, can improve cycling performance across a range of durations by buffering exercise-induced acidosis, suggesting efficacy across a range of cycling disciplines in which both intermittent and sustained high power outputs are required. Practical use may require strategies like enteric capsules or co-ingestion with carbohydrates to reduce common gastrointestinal discomfort. Although we are unaware of any adverse effects associated with chronic loading at doses ranging from 0.3 to 0.5 mg/kg BM over 5 days (Douroudos et al., 2006; McNaughton, Backx, et al., 1999) or 0.4 mg/kg BM three times per week for 8 weeks (Edge et al., 2006), practitioners should carefully monitor blood responses (e.g., acid-base and sodium content) for the safety of the athlete if repeated doses are taken given the relatively high sodium load (~0.274 g sodium/g sodium bicarbonate or ~0.235 g sodium/g trisodium citrate).

Beta-Alanine

Chronic BA supplementation has gained considerable attention in sport nutrition, with particular interest for cycling. BA, an amino acid, is the rate-limiting precursor for increasing the concentration of carnosine in skeletal muscle (Boldyrev, 1993). Indeed, Harris et al. (2006) and Hill et al. (2007) demonstrated that the chronic ingestion of BA (6.4 g/day) for 4–10 weeks can substantially elevate muscle carnosine stores by 50%–80%. Smaller doses (i.e., 3.2 g/day) can also increase muscle carnosine content (~37%–50%), but this typically requires a longer supplementation period to fully saturate the muscle (Stegen et al., 2013). In contrast to sodium bicarbonate, which buffers pH in blood (i.e., an extracellular buffer), carnosine counteracts H⁺ accumulation within skeletal muscle (i.e., an intracellular buffer) during high-intensity exercise and therefore can improve performance during exercises for which acidosis may negatively impact performance (Hill et al., 2007).

Studies evaluating the ergogenic potential of BA supplementation in cycling suggest efficacy for exercise with a duration of 1–10 min (Saunders, de Oliveira, et al., 2017). Although carnosine loading can attenuate acidosis during a 6-min high-intensity cycling test, BA is probably not ergogenic in aerobic constant-load exercise of longer duration, such as a time trial of about 1 hr duration (Chung et al., 2014). However, in laboratory-based studies simulating a cycling race of several hours concluding with a high-intensity finale (e.g., either a final sprint or a 4-km time trial), BA

supplementation has demonstrated mixed results, with some (Van Thienen et al., 2009) but not others (Perim et al., 2022) showing a positive effect on performance. Repeated high-intensity sprints, such as 30-s Wingate tests, with incomplete recovery may also be augmented by enhanced carnosine content via BA loading (de Salles Painelli et al., 2014).

Critically, the ergogenic effect of BA supplementation has also been investigated and confirmed in well-trained cyclists (i.e., Tier 2–3, amateur, semiprofessional) with maximum aerobic capacity ($\dot{V}O_2\text{max}$) in the range of 60–70 ml·kg⁻¹·min⁻¹ (Howe et al., 2013; Bellinger & Minahan, 2016). Specifically, BA supplementation improved performance compared with placebo during both a supramaximal time to exhaustion test (8%) and a 4-km time trial (~2%), whereas 10-km time-trial performance (Bellinger & Minahan, 2016) and mean power output during a 4-min time trial (Howe et al., 2013) were not different. Interestingly, the time to complete an uphill time trial (4.5 km at 5% gradient) was also improved (3%) in professional (World Tour, Tier 4+) cyclists supplementing with BA for only 7 days, with no change in mean power output (Pérez-Piñero et al., 2024). Common side effects include paresthesia (tingling) of the skin (Harris et al., 2006); however, this can be avoided by using smaller, more frequent doses throughout the day (Derave et al., 2007; Hill et al., 2007) or by using slow-release capsules (Stellingwerff et al., 2012). Critically, current evidence suggests that long-term (24 weeks) supplementation with 6.4 g/day BA is well-tolerated and safe and did not result in any adverse clinical outcomes or chronic sensory effects (Dolan, Swinton, et al., 2019; Saunders et al., 2020). Collectively, the evidence indicates that BA can augment skeletal muscle carnosine levels, delaying fatigue during high-intensity efforts in cycling, making it a useful tool for events with decisive short, intense segments.

Dietary Inorganic Nitrate

Nitric oxide (NO) is a potent signaling molecule that exerts a variety of regulatory effects across different biological systems. NO can be produced endogenously via oxidation of L-arginine (Moncada & Higgs, 1993) or via the sequential reduction of dietary inorganic nitrate (NO_3^-) and nitrite (NO_2^-) consumed through food stuffs including dark leafy green vegetables, which contain ~4 mmol NO_3^- per 100 g (Hord et al., 2009). The conversion of nitrate to nitrite is facilitated by commensal bacteria in the oral cavity, which may be affected by the use of antibacterial agents such as mouthwash (Govoni et al., 2008). More recently, it has been demonstrated that skeletal muscle has a higher nitrate concentration than blood (Jones et al., 2021), suggesting that this reservoir may play an important role in the localized production and utilization of NO during exercise (Nyakayiru et al., 2017; Wylie et al., 2019). Interest in the use of nitrates as supplements to improve athletic performance stems from early work showing that supplementation with either sodium NO_3^- (0.1 mmol·kg BM⁻¹·day⁻¹) (Larsen et al., 2007) or nitrate-rich beetroot juice (5.6 mmol/day NO_3^-) (Bailey et al., 2009) for 3 days resulted in a 3%–5% reduction in pulmonary oxygen consumption ($\dot{V}O_2$) for a given power output during submaximal cycling. Critically, this suggests that nitrate allows for a greater amount of external work to be done per unit of time for the same absolute oxygen cost. Although it was initially believed that this increase in exercise efficiency was driven by improved mitochondrial efficiency (i.e., an increase in the amount of ATP relative to the amount of oxygen consumed) (Larsen et al., 2011), this has not been

replicated in subsequent studies (Ntessalen et al., 2020; Whitfield et al., 2016). Nitrate supplementation may instead target actomyosin ATPases and the sarcoendoplasmic reticulum calcium ATPase, the two largest sources of energy consumption during exercise. In support of this, several studies have demonstrated an improvement in skeletal muscle contractile function following acute (Coggan et al., 2015; Wickham et al., 2019) and chronic nitrate supplementation (Haider & Folland, 2014; Whitfield et al., 2017; Wickham et al., 2019), while energy (ATP and PCr) turnover during leg extension exercise has also been shown to be lower after consuming beetroot juice for 6 days (5.1 mmol/day) (Bailey et al., 2010). These effects are proposed to be mediated by changes in skeletal muscle calcium handling and/or sensitivity (Coggan & Peterson, 2018; McIlvenna et al., 2020); however, more work is required to confirm this hypothesis.

Several meta-analyses have confirmed that nitrate supplementation can improve endurance exercise performance (McMahon et al., 2017; Pawlak-Chaouch et al., 2016; Senefeld et al., 2020), with typical doses of ~6 mmol being consumed in the 2–3 hr prior to exercise (Table 2). The improvement in exercise efficiency (i.e., increased power output or work for the same oxygen cost) makes nitrate an attractive supplement for most disciplines in cycling relying on aerobic capacity (i.e., road, endurance track, mountain biking, cyclo-cross, etc.). Equally, the possibility of improving calcium handling and contractile function suggests that other more explosive disciplines (e.g., BMX [Haakonssen et al., 2025 in review], sprint track [Stanley et al., 2025 in review], etc.) requiring rapid production of very high power outputs also stand to benefit. However, questions have been raised about whether it is a viable ergogenic aid for elite athletes (Jonvik et al., 2015). This concern is supported by a recent meta-analysis showing no ergogenic effect for individuals with a $\dot{V}O_2\text{max} \geq 65$ ml·kg⁻¹·min⁻¹ (Senefeld et al., 2020) and a dose–response relationship based on aerobic fitness (Porcelli et al., 2015). This finding may be due to higher endogenous nitrate levels among elite athletes in combination with chronic adaptations induced by training. Future work is required to determine if higher doses (e.g., 8.4–16.8 mmol) of nitrate or longer supplementation periods (e.g., 5–15 days) create benefits in elite athletes. Female athletes may have different responses to nitrate supplementation compared with males (Wickham & Spriet, 2019). Although studies of nitrate supplementation in females are limited, the current literature fails to support an overall positive effect on performance in females (Senefeld et al., 2020). In summary, nitrate supplementation can improve cycling performance by improving skeletal muscle efficiency and function. Questions remain about its efficacy among elite athletes, suggesting it may be a more beneficial among developing athletes or subelite athletes (i.e., ≤Tier 3). Additional research is also required to determine its effectiveness in female athletes. Practical challenges like poor taste and interference from the use of antibacterial mouthwash should be considered.

Hyperhydration and Cycling Performance

Significant fluid loss through sweating (i.e., dehydration) imposes thermoregulatory and cardiovascular strain, potentially impairing cycling performance and increasing the risk of heat-related illnesses (Cheuvront & Kenefick, 2014). However, inducing water retention (also known as hyperhydration) prior to exercise through the use of nutritional supplements, such as glycerol (Anderson et al., 2001) and sodium loading (Nelson et al., 2008), can increase total body water content. This includes an expansion of plasma

volume (hypervolemia), which can offset some of the fluid lost as sweat loss that cannot be compensated by fluid intake during exercise (Goulet et al., 2018). Consuming large amounts of water alone prior to exercise is ineffective for inducing hyperhydration as it reduces serum osmolality, suppresses vasopressin release, and ultimately leads to the rapid elimination of excess water through urine (Viinamäki, 1990).

Recent meta-analyses suggest that preexercise hyperhydration reduces heart rate and core temperature during constant-intensity exercise (Jardine et al., 2023) and elicits a small to moderate improvement in cycling performance in both time trials and time-to-exhaustion activities (Jardine et al., 2023; McCubbin & Irwin, 2024), particularly when performed in the heat (Anderson et al., 2001; Morris et al., 2015). As such, this may be a valuable approach for endurance-based UCI events such as road cycling (Jeukendrup et al., 2025 in review), mountain biking (Oosthuyse et al., 2025 in review), and gravel racing (Whitfield et al., 2025 in review), but is less advisable for shorter endurance events (i.e., <1 hr) or those performed in cooler or thermoneutral conditions as the benefits are likely to be of lower magnitude in these scenarios. However, these effects vary depending on the agent used, with glycerol promoting both intra- and extracellular fluid retention and sodium loading predominantly enhancing extracellular and hypervolemia (McCubbin & Irwin, 2024).

Glycerol is a three-carbon alcohol absorbed in the gastrointestinal tract and distributed across intra- and extracellular compartments, creating an osmotic gradient that promotes fluid retention and reduced urine production (Anderson et al., 2001). Glycerol was banned by the World Anti-Doping Agency (WADA) in 2010 due to potential risks associated with masking blood doping; however, it was removed from the prohibited list in 2018 and now has a robust body of evidence supporting its efficacy (Goulet et al., 2007; Jardine et al., 2023; McCubbin & Irwin, 2024). Systematic reviews and meta-analysis have found that ingestion of 1.0–1.5 g/kg BM of glycerol in combination with a fluid load (~25 ml/kg BM, equivalent to 2.5% of BM) (Table 2) can increase fluid retention by ~40% (Goulet et al., 2018) and improve cycling performance by ~2%–5% (Goulet et al., 2007; Jardine et al., 2023; van Rosendal et al., 2009) by promoting higher cycling power output without an associated increase in perception of effort (Hitchins et al., 1999). However, excessive doses of glycerol during hyperhydration may cause side effects including gastrointestinal issues such as bloating and nausea (Jardine et al., 2023), highlighting the need for individual tolerance assessment and adherence to recommended protocols. Considerations should also be made with respect to an increase in BM and what impact that may have on power-to-weight ratios and race outcomes.

Sodium chloride and sodium citrate are also effective at inducing preexercise hyperhydration due to their ability to promote fluid retention by increasing extracellular osmolality (Morris et al., 2015; Nelson et al., 2008). Consuming these salts in capsule form (3–8 g of sodium chloride or 2–4 g of sodium citrate, Table 2) with a large volume of water has been shown to enhance fluid retention and maintain electrolyte balance. Alternatively, athletes may consume salted drinks (~10 ml/kg BM of 120–180 mEq of sodium drink), although consuming high volumes can be challenging due to the taste of the drink (Pérez-Castillo et al., 2023). Sodium-induced hyperhydration has been demonstrated to improve cycling performance, especially in the heat (Morris et al., 2015; Sims et al., 2007), by sustaining plasma volume, reducing core temperature increases, and mitigating dehydration-induced fatigue. However, excessive sodium loading can lead to gastrointestinal discomfort,

increased thirst, and, in extreme cases, hypernatremia. It is noted that sodium load involved in sodium bicarbonate/citrate supplementation is similar to the amount used as an osmolyte in hyperhydration strategies (Siegler et al., 2022). Therefore, in some scenarios, riders could combine hyperhydration and buffering strategies (outlined above) as long as the desired timing of the dosing protocol for each strategy coincided. The combination of glycerol and sodium hyperhydration merits further investigation as this may result in greater fluid retention (>70%; Goulet et al., 2018). In summary, for cyclists competing in long, high-intensity events, strategic preexercise hyperhydration using glycerol or sodium salts can help sustain plasma volume, reduce thermal strain, and improve performance, particularly in hot conditions. However, due to their mechanisms of action, these substances can commonly cause gastrointestinal discomfort and may be associated with an increase in BM, so protocols should be individualized to optimize benefits while minimizing side effects.

Exogenous Ketone Supplements

Ketone bodies (KBs) are lipid-derived compounds including β -hydroxybutyrate (β -HB) and acetoacetate that are produced endogenously by the liver and whose production is amplified during periods of energy and/or carbohydrate restriction (e.g., prolonged fasting or adherence to a low-carbohydrate diet). Nutritional ketosis is typically defined as circulating [β -HB] ≥ 0.5 mM (Volek et al., 2015). Recently, ingestible supplements in the form of ketone salts and esters (including mono- and diesters) have been developed to exploit the metabolic effects of ketosis in the absence of severe energy and carbohydrate restriction. Although exogenous ketone supplements are currently classified as “Group B” in the AIS Framework (i.e., requiring additional research), they have been the subject of much interest in the past decade (Evans et al., 2022) and have been the source of considerable discussion and controversy in professional cycling, leading the Movement for a Credible Cycling to recommend that its members in professional sport avoid using them because of concerns about health and fairness (Debruyne, 2024). As a result, they are discussed in detail here, with key studies exploring ketone use in cycling highlighted in Table 3.

Ketone salts are typically a mixture of the two naturally occurring forms of beta-hydroxybutyrate (D- β -HB and L- β -HB), bound to mineral salt(s) such as calcium, sodium, or potassium (Evans et al., 2022). This form of exogenous ketone supplement is less effective at increasing D- β -HB (Stubbs et al., 2017), the predominant KB that is metabolized by extrahepatic tissues including skeletal muscle (Rijt et al., 2021; Tsai et al., 2006). Ketone salts have been associated with side effects including nausea and gastrointestinal upset (Evans et al., 2018; Stubbs et al., 2019). By contrast, ketone esters are salt-free and generally well-tolerated and induce a rapid (minutes to hours) dose-responsive increase in D- β -HB following ingestion (Clarke et al., 2012; Cox et al., 2016; Shivva et al., 2016; Stubbs et al., 2017). The majority of research on exercise performance and metabolism has focused on the ketone monoester (R)-3-hydroxybutyl (R)-3-hydroxybutyrate (KME), which is produced by the esterification of D- β -HB and a ketogenic precursor known as R-1,3-butanediol. Indeed, the R-1,3-butanediol molecule in isolation is also commercially available as an exogenous ketone supplement, but to date it has been shown to have little impact on cycling performance (Shaw et al., 2019).

Because of the multiple actions of KBs and the marked effects of nutritional ketosis on metabolism (Poff et al., 2020; Puchalska &

Table 3 Summary of Studies of Acute Ingestion of Exogenous Ketone Supplements on Cycling Performance in Trained Athletes

Author	Participant profile	Exercise protocol and performance test	Supplement type, dose, timing and conditions	Performance outcome
Shaw et al. (2019)	Nine male cyclists Hours training per week, 12.3 ± 2.3 hr $\dot{V}O_2\text{max}$, 63.9 ± 2.5 ml·kg ⁻¹ ·min ⁻¹	85-min cycling (85% VT ₂ ; 73.0 ± 5.2% $\dot{V}O_2\text{max}$) 7 kJ/kg TT	BD BD: 0.7 g/kg BD PLA: Noncaloric placebo Split (50:50; –30 min preexercise and 60 min into exercise)	No significant difference between PLA and BD Time to complete (min): BD: 28.7 ± 3.2 PLA: 28.5 ± 3.6
Rodger et al. (2017)	12 male cyclists Professional, A or B-grade cyclists $\dot{V}O_2\text{max}$, 68.0 ± 6.7 ml·kg ⁻¹ ·min ⁻¹	90-min cycling (80% VT ₂) 4-min maximal performance cycling test	KS KS: 23.4 g R,S-βHB PLA: Noncaloric placebo Split (50:50; –20 min preexercise, 45 min into exercise)	No significant difference between PLA and KS Average power output (W): KS: 355 ± 46 PLA: 364 ± 58
Cox et al. (2016)	Eight endurance athletes (six males, two females) $\dot{V}O_2\text{max}$, M: 5.37 ± 0.3 L/min; F: 3.30 ± 0.1 L/min	60-min cycling (75% W _{max}) 30-min cycling TT (max distance)	R-BD R-βHB KME KME: 573 mg/kg KME (40% of total energy intake) + 1.2 g/min CHO PLA: Isocaloric CHO as 40% dextrose, 40% fructose, 20% maltodextrin Multiple (50:25:25, –20 min preexercise, 30 and 60 min into exercise)	↑ performance in KME vs. PLA Distance covered (m): ~20,000 m in PLA, but 411 ± 162 m (mean ± SEM) further* in KME
Leckey et al. (2017)	10 male cyclists, internationally competitive $\dot{V}O_2\text{max}$, 71.4 ± 5.6 ml·kg ⁻¹ ·min ⁻¹	4 × 5 min cycling as standardized warm-up 31.17-km cycling TT	R,S-BD AcAc KDE: 500 mg/kg KDE + 250 ml 6% CHO drink PLA: 250 ml 6% CHO drink Split (50:50; –30 and –5 min preexercise)	↓ performance in KDE vs. PLA Average power output (W) KDE: 339 ± 37* PLA: 352 ± 35 ES: 0.42 (small)
Dearlove et al. (2019)	12 healthy athletes (nine males, three females) Minimum 6 hr endurance training per week $\dot{V}O_2\text{max}$, 4.4 ± 0.2 L/min	Incremental cycling test to exhaustion	R-BD R-βHB KME KME: 330 mg/kg KME PLA: Noncaloric placebo Single (–60 min preexercise)	No significant difference between PLA and KME Peak power output (W) KME: 393 ± 22 PLA: 389 ± 20
	12 highly trained male cyclists $\dot{V}O_2\text{max}$, 62.4 ± 6.6 ml·kg ⁻¹ ·min ⁻¹	180-min cycling (6 × 30 min blocks at varying intensities) 15-min cycling TT followed by sprint cycle to exhaustion (175% LT W)	R-BD R-βHB KME KME: 65 g (918 ± 102 mg/kg KME) + 60 g/hr CHO PLA: Taste- and volume-matched CP + 60 g/hr CHO Multiple (25/20/20 g; –60 and –20 min preexercise, 30 min into exercise)	No significant difference between PLA and KME Average power output (W) in TT: KME: 273 ± 38 PLA: 272 ± 37 TTE in sprint (s): KME: 59 ± 16 PLA: 58 ± 17
Poffé, Ramaekers, et al. (2021)	Nine trained male cyclists $\dot{V}O_2\text{max}$, 61.0 ± 2.9 ml·kg ⁻¹ ·min ⁻¹	180-min cycling (6 × 30 min blocks at varying intensities) 15-min cycling TT followed by sprint cycle to exhaustion (175% LT W)	R-BD R-βHB KME KME: 65 g (922 ± 85 mg/kg) KME + 60 g/hr CHO BIC: Taste- and volume-matched CP + 60 g/hr CHO + 300 mg/kg BIC KME + BIC: as above, combined PLA: Taste- and volume-matched CP + 60 g/hr CHO Multiple (25/20/20 g; –60 and –20 min preexercise, 30 min into exercise)	↑ performance in KME + BIC for average power output, but not TTE in sprint Average power output (W) in TT: ~5% (~12 W) higher* in KME + BIC compared with PLA, KME, and BIC (all ~254 W) ES: 0.77–1.01 (medium-large) TTE (s) in sprint: KME: 55 ± 19 BIC: 58 ± 19 KME + BIC: 58 ± 21 PLA: 55 ± 21
Poffé, Wyns, et al. (2021)	12 highly trained, male cyclists $\dot{V}O_2\text{max}$, 62.5 ± 5.5 ml·kg ⁻¹ ·min ⁻¹	60-min standardized warm-up 30-min cycling TT followed by sprint cycle to exhaustion (175% LT W)	R-BD R-βHB KME KME: 50 g KME (726 ± 75 mg/kg) + 60 g/hr CHO BIC: Taste- and volume-matched CP + 60 g/hr CHO + 180 mg/kg BIC KME + BIC: as above, combined PLA: Taste- and volume-matched CP + 60 g/hr CHO Split (50:50; during warm-up as –30 and –5 min pre-TT)	↓ performance in KME Average power output in TT: 3.8 ± 1.5 W lower* in KME and KME + BIC than BIC and PLA ES: 0.13 (small) TTE in sprint not different between KME and PLA, but was 5 ± 1 s longer* in BIC and KME + BIC (–69 s) than KME and PLA (–64 s)

(continued)

Table 3 (continued)

Author	Participant profile	Exercise protocol and performance test	Supplement type, dose, timing and conditions	Performance outcome
Poffé, Robberechts, et al. (2021)	14 highly trained male cyclists $\dot{V}O_2\text{max}$, $64.6 \pm 6.6 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$	180-min cycling (6 × 30 min blocks at varying intensities) 15-min cycling TT followed by sprint cycle to exhaustion (175% LT W) Trials performed in hypobaric altitude Hypobaric altitude began increasing at start of exercise, peaked at 3,000 m at 150 min into exercise	R-BD R-βHB KME KME: 75 g ($1,019 \pm 111 \text{ mg/kg}$ KME) + 60 g/hr CHO BIC: Taste- and volume-matched CP + 60 g/hr CHO + 300 mg/kg BIC KME + BIC: as above, combined PLA: Taste- and volume-matched CP + 60 g/hr CHO Multiple (25/25/25 g; 30, 90, and 150 min into exercise)	No significant difference between conditions Average power output (W) in TT: KME: 248 ± 21 BIC: 248 ± 21 KME + BIC: 249 ± 25 PLA: 246 ± 26 TTE in sprint not different between conditions
McCarthy et al. (2021)	19 endurance-trained individuals (10 males, nine females) Endurance training ≥ 3 times per week $\dot{V}O_2\text{max}$, M $61 \pm 7 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$; F $53 \pm 6 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$	30-min cycling at VT ($71 \pm 3\% \dot{V}O_2\text{max}$) followed by 15-min rest prior to a 3 kJ/kg cycling TT	R-BD R-βHB KME KME: 600 mg/kg KME + 25 g sports drink powder PLA: Flavor-matched PLA + 25 g sports drink powder Single (–35 min preexercise)	No significant difference between KME and PLA Average power output (W), median (IQR): KME: 196 (176–295) PLA: 201 (174–279) Time to compete (min:s): KME: $16:25 \pm 2:50$ PLA: $16:06 \pm 2:40$
Robberechts et al. (2022)	11 well-trained male cyclists $\dot{V}O_2\text{max}$, $60.2 \pm 5.6 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$	180-min cycling (6 × 30 min blocks at varying intensities) 15-min cycling TT followed by sprint cycle to exhaustion (175% LT W) Trials performed in 28 °C and 60% relative humidity	R-BD R-βHB KME KME: 65 g ($892 \pm 94 \text{ mg/kg}$ KME) + 60 g/hr CHO PLA: Taste- and volume-matched CP + 60 g/hr CHO Multiple (25/20/20 g; –60 and –20 min before exercise, and 30 min into exercise)	No significant difference between KME and PLA Average power output (W) in TT: KME: 297 ± 38 PLA: 297 ± 40 TTE in sprint: KME: $54 \pm 11 \text{ s}$ PLA: $53 \pm 12 \text{ s}$
McCarthy et al. (2023)	23 trained cyclists (21 males and two females) $\dot{V}O_2\text{max}$, $65 \pm 12 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$	15-min self-directed warm-up followed by 20-min cycling TT	R-BD R-βHB KME KME: 350 mg/kg KME PLA: Flavor-matched isocaloric Single (–30 min preexercise)	↓ performance in KME vs. PLA Average power output (W) in TT: 2.4% (0.6%–4.1%) lower* KME: $255 \pm 54 \text{ W}$ PLA: $261 \pm 54 \text{ W}$ ES: 0.60 (medium)
Ramos-Campo et al. (2023)	28 male World Tour cyclists $\dot{V}O_2\text{max}$, $70.8 \pm 0.7 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$	Road cycling simulation composed of 8-min TT performance + 30 s TT followed by 4.5 hr of outdoor cycling 8-min TT + 30 s TT	R-BD R-βHB KME KME: 800 mg/kg KME + 90 g/hr CHO PLA: Taste- and volume-matched + 90 g/hr CHO BIC consumed in both conditions Split (50:50; –30 min preexercise and +90 min after starting exercise)	↑ performance in KME vs. PLA Average power output was 3.1% higher* during the first 8-min TT with KME (389 ± 34 vs. $378 \pm 44 \text{ W}$; 5.60 ± 0.42 vs. $5.41 \pm 0.44 \text{ W/kg}$)

Note. All data are mean $\pm$ SD unless otherwise stated. ES are calculated as Cohen's *d*. Bolded text is the supplement type. BD = 1,3-butanediol; BIC = sodium bicarbonate; CHO = carbohydrate; CP = collagen peptides; ES = effect size; IQR = interquartile range; KDE = R,S-BD AcAc ketone diester; KS = ketone salts; KME = R-BD R-βHB ketone monoester; R-BD R-βHB = (R)-3-hydroxybutyl (R)-3-hydroxybutyrate; R,S-BD AcAc = R,S-1,3-butanediol acetoacetate; LT = lactate threshold; PLA = placebo condition; SEM = standard error of the mean; TT = time trial; TTE = time to exhaustion; $\dot{V}O_2\text{max}$ = maximum rate of oxygen uptake; VT = ventilatory threshold.

* $p < .05$ for the exogenous ketone supplement compared with PLA or control condition.

Crawford, 2021), exogenous ketone supplements may be employed as an ergogenic aid in cycling through preexercise ingestion to improve exercise acutely or through ingestion after exercise to enhance subsequent recovery and/or adaptation (Evans et al., 2022). Three interrelated mechanisms have been proposed for the putative ergogenic action of KBs: they may provide an alternative metabolic fuel or substrate for working muscle (Cox et al., 2016) with increased efficiency of ATP production when oxidized (Murray et al., 2016; Sato et al., 1995; Veech, 2014) and, therefore, reduce reliance on carbohydrate utilization during exercise (reviewed in Evans et al., 2022). However, more recent work utilizing a bespoke ^{13}C -labeled ketone ester tracer demonstrated that the contribution of β-HB to overall exercise energy expenditure is

minimal (2%–5%; Dearlove et al., 2021). Mechanistic work in human muscle fiber bundles has supported this finding by showing minimal mitochondrial utilization of KBs to produce energy compared with carbohydrate-derived substrates (Petrick et al., 2020). The effects of ingestion of the KME on muscle glycogen or intramuscular triglyceride utilization during exercise are also inconsistent (Cox et al., 2016; Poffé et al., 2020).

Studies evaluating changes in cycling-specific performance following the ingestion of ketones have largely been mixed (Table 3). The first study of the KME on performance demonstrated a 2% improvement in a 30-min time-trial performed after a 60-min preload (Cox et al., 2016). Subsequent work combining the KME with sodium bicarbonate has yielded some positive results on acute

performance, including a 5% improvement in 15-min time trial conducted after 3 hr of race simulation (Poffé, Ramaekers, et al., 2021) and a ~3% improvement in mean power output during a 8-min time trial performed by World Tour (i.e., Tier 4–5) cyclists (Ramos-Campo et al., 2023). However, many studies have observed null effects, and decrements in time-trial performance have also been observed. Ingestion of a R,S-BD acetoacetate ketone diester decreased time-trial performance in elite (Tier 4–5) cyclists by ~2% (Leckey et al., 2017), and the average power output following supplementation with KME was 2.4% and 1.5% lower during 20 (McCarthy et al., 2023) and 30 min (Poffé, Wyns, et al., 2021) time trials, respectively (Table 3). As a result, there is currently not a strong evidence base to support the use of ketone esters to acutely improve same-day performance.

In contrast to exercise performance, there is a growing body of literature exploring the effects of exogenous ketone supplements on recovery and adaptative responses to exercise (Robberechts & Poffé, 2024). Although the effects of KME ingestion on postexercise glycogen resynthesis are mixed (Holdsworth et al., 2017; Vandoorne et al., 2017), augmenting postexercise KB concentrations may increase the cell signaling responses associated with muscle protein synthesis (Vandoorne et al., 2017). Recent work directly comparing muscle protein synthesis responses in a fasted, resting state following the ingestion KME (~25 g), whey protein (10 g), or a combination of the two showed that all three treatments increased protein synthesis above basal levels, but no difference was detected between treatments (Hannaian et al., 2024). Future work is therefore required to explore how exercise impacts these results in order to translate the findings for athletes.

Another emerging area of interest is the impact of KBs on erythropoietin, a hormone that plays a central role in the production of red blood cells and oxygen-carrying capacity, which is highly relevant for cycling performance. Two recent studies have demonstrated that acute ingestion of the KME after exercise resulted in a ~20%–25% increase in serum erythropoietin concentrations over 4 (Evans et al., 2023) and 12 hr (Poffé et al., 2023). Daily KME ingestion during a 3-week endurance cycling overload mimicking a Grand Tour has also been suggested to blunt the development of overreaching symptoms and augment time-trial performance (Poffé et al., 2019), with a follow-up analysis also showing increased markers of angiogenesis in response to the training intervention (Poffé et al., 2023). However, some concern has been expressed over the interpretation of these findings (Bellinger, 2019; Korevaar et al., 2019; Mullie & Autier, 2019) as the group supplementing with ketones spontaneously increased their daily energy intake by ~20%, largely due to greater amounts of daily carbohydrate intake (+25.5% vs. baseline intake at Week 2 and +29.9% at Week 3). As such, it is currently unclear whether the blunting of overtraining symptoms demonstrated (Poffé et al., 2019) was due to ketone ingestion or simply due to an overall increase in energy and carbohydrate intake, which itself would be expected to support a higher training load and performance. Regardless, given the potential issues with low energy availability in cyclists (Burke, Gonzalez et al., 2025), longer term studies with dietary control are required to determine how exogenous ketone supplements may regulate appetite and energy intake in cyclists (Stubbs et al., 2018), whether the small transient increases in erythropoietin translate to increases in hemoglobin and hematocrit concentrations, and whether postexercise ingestion of exogenous ketone supplements has any impact on recovery and adaptation to exercise training. In summary, the current evidence does not support the widespread use of exogenous ketone supplements to

improve same-day performance. Further research is needed to clarify their long-term impact, especially in the context of energy availability, recovery, and elite competition.

Contemporary Applications for Supplements to Improve Performance in Cycling

Many of the performance supplements considered to be evidence based have been utilized by athletes for decades. However, in many instances, research studies evaluating their effect(s) have failed to recognize the complexity and specificity of the demands of high-performance cycling. There is therefore a need for further research as well as case-study observations of real-world applications of performance supplements in cycling. These include consideration of the format of many cycling events, different responses across cohorts of cyclists (e.g., based on biological sex, training level, and/or age), the interaction between supplements when taken simultaneously, and the use of supplements for training adaptation and recovery in addition to their effects on race performance. For example, given the multitude of supplements marketed toward athletes promising beneficial effects for performance, it is perhaps unsurprising that cyclists may elect to co-ingest multiple supplements in the hopes of synergistic or additive effects. Although the list of possible combinations and dosing strategies prevents us from exploring all possible applications (for a review, see Burke, 2017; Zart & Fröhlich, 2025), athletes should consider targeted approaches combining supplements with a potential common mechanism of action (e.g., better maintenance of pH balance when sodium bicarbonate and BA are combined), potentially additive effects of two separate mechanisms of benefit (e.g., combination of caffeine and nitrate), and positive synergistic effects (e.g., sodium bicarbonate countering the acidification associated with exogenous ketone supplementation as outlined above). Conversely, athletes may need to consider the possibility of negative synergistic effects (e.g., sodium bicarbonate buffering of extracellular pH reducing the conversion of nitrate to NO and limiting the potential effects of nitrate supplementation) and overall negative effects (e.g., gastrointestinal distress with the combined use of caffeine and sodium bicarbonate). Table 4 summarizes our understanding of these more nuanced issues.

Pros and Cons of the Use of Sports Foods and Supplements

The popularity of use of sports foods and supplements among cyclists is supported by the benefits that may occur through effective delivery of nutrient and energy targets as well as, in a few cases, direct ergogenic effects. However, a number of concerns and limitations around their use have also been identified (Burke & Slater, 2021). Table 5 summarizes such pros and cons, with a focus on common scenarios that arise among the cycling disciplines. Safety and the financial burden are key issues among the potential downsides of sports foods and supplements. For example, in some cycling disciplines, the number of hours spent on the bike in training and racing each year would create a substantial bill if fueled entirely by sports foods/drinks. Therefore, many cyclists include everyday foods (e.g., sandwiches, fruit, cakes, confectionary, etc.) within training rides to reduce cost (and flavor fatigue) and limit their use of more expensive sports foods to race scenarios.

Table 4 Contemporary Issues in Use of Evidence-Based Performance Supplements in Cycling

Issue	Context	Recommendations and examples
Concurrent use of multiple supplements	• Some studies evaluating the combined use of supplements with highly trained cyclists and cycling-specific protocols exist (Bellinger et al., 2012; Lane et al., 2014); however, there are countless permutations of different combinations of supplements and dosing strategies. • Accordingly, not all strategies have been robustly evaluated, meaning there is not large cohort-based data sets to draw conclusions from. • Difficulty in isolating effects in $n = 1$ individual experimentation.	• More research is needed on the effects of the combined use of evidence-based performance supplements and cycling-specific scenarios. • A Latin squares application of treatments in a crossover-designed study can provide a robust and practical framework for investigating the single and combined effect of two acutely administered products (Burke & Peeling, 2018). • Simultaneous use of several performance supplements within a cyclist's nutrition plan may be practically managed using single case and small group observations, with intuition and experience also guiding the process (Burke, 2017). • In some instances (e.g., resource issues or scheduling difficulties), combined use of supplements may not be possible. Priority should be given to the product that is likely to achieve the greatest or most consistent performance benefit.
Repeated use of supplements for rounds and multiple events	• While many cycling events involve repeated competition (e.g., road cycling stage races, rounds in track cycling and BMX or components of multievent cycling eSports competition), the current literature on consuming multiple doses of supplements in cycling is very sparse. • Performance responses may therefore be dictated by overall race scheduling, as repeated doses may be needed to maintain or repeat the benefits. • Depending on the half-life of the supplement, its subsequent use might require a different protocol to restore the physiological advantage or to meet the logistical requirements of competition spacing. • Individuals should consider whether repeated/habitual use may lead to desensitization and therefore decreased effectiveness of the supplement, as well as what subsequent impact this may have on recovery (e.g., the effects of caffeine on subsequent sleep).	• Different dosing strategies may be required according to the characteristics of the event and the recovery time between races. • Sodium bicarbonate ingestion prior to exercise may prove beneficial for enhancing performance across multiple bouts of exercise when the recovery period is short (i.e., <60 min). Additional ingestion postexercise may accelerate the acid-base recovery process, thereby enhancing subsequent performance (Gurton et al., 2024). • Evidence from other sports that the performance benefits of caffeine is maintained when it is used on sequential days of competition (Stadheim et al., 2014). • While further research is encouraged, single case and small group observations during training or lower level/simulated racing may help to develop successful plan. • When there is doubt, it may be prudent to save or target the use of a performance supplement to the final or most important race.
Strategic use of supplements within a long event to target key periods	• Long-duration cycling events (e.g., road or gravel races) contain single or multiple pivotal moments targeted for performance boost (e.g., decisive climbs, intermediate and final sprints, breakaways, etc.). • However, the duration of these events may extend beyond the effective half-life of a supplement if ingested prior to exercise.	• As part of race planning, cyclists should identify key periods where peak action of a performance supplement is desirable. • Prior to racing, cyclists should develop a utilization plan, including an understanding of the kinetics of their personal use of a supplement (e.g., time between taking the dose and achieving a performance boost; the duration of the effect, any side effects). • Application of this understanding may allow individuals to alter the timing of ingestion for products conventionally taken well prior to event, including consuming doses within the race itself. • Such strategies have been used to improve performance in the latter stages of prolonged cycling using both caffeine (Cox et al., 2002) and sodium bicarbonate. • Prioritize supplement forms that can be easily consumed while riding (i.e., contained within race nutrition supplies) or rapidly absorbed to achieve their effect (e.g., caffeine gum or strips that are absorbed via the buccal cells in the mouth).

(continued)

Table 4 (continued)

Issue	Context	Recommendations and examples
Use as a training aid	• Cyclists across many disciplines may train in excess of 20 hr per week (Valenzuela et al., 2025), presenting ample opportunities to employ ergogenic supplements prior to targeted training sessions to enhance adaptations. • Higher quality performance, including support during sessions that are undertaken in a fatigued state, may improve specific race preparation.	• Implement supplements into the training plan to improve the quality of high-intensity sessions or attenuate the fatigue associated with some training modalities. • For example, sodium bicarbonate supplementation prior to training (3× a week for 8 weeks) led to greater improvements in exercise capacity vs. training alone (Edge et al., 2006). • Creatine (Forbes et al., 2023; Kreider, 2003) and BA (Maté-Muñoz et al., 2018; Milioni et al., 2019) may also similarly enhance training adaptations by increasing power output and attenuating fatigue during training; however, cycling-specific research is required. • Periodized use of caffeine within training phases has been examined from a theoretical perspective (Pickering & Grgic, 2021) and is effective in targeted sessions (Lane et al., 2013). • Consistent practice of supplement strategies (including using those intended for race day) may increase the rider's insight on individual responsiveness and help to fine tune race plans.
Effects on cognitive performance	• Majority of studies on supplements and cycling have focused on measures of physical performance (e.g., power, time to complete a task); however, many cycling disciplines require rapid decision making and tactical adjustments (e.g., choice of line in mountain biking, positioning and maneuvering in the peloton during a sprint). • Several supplements are known or proposed to enhance cognitive performance, especially when this is impaired or under increased stress that could be associated with cycling such as with prolonged exertion, sleep deprivation, hypoxia, or TBI (e.g., following a crash).	• Many cycling events require high levels of skill and rapid decision-making due to their tactical nature. This may be challenged by accumulated fatigue from sustained exertion in stage races, intensified training or sleep deprivation, or by TBI as a result of crashing. Targeted research on the effects of supplements on cognitive performance and its transfer to race performance and/or better-quality training is therefore warranted. • Creatine may be used to enhance brain function and cognition (Borchio et al., 2020; Guest et al., 2021) and attenuate the effects of TBIs (Dolan, Gualano, & Rawson, 2019). • There is evidence that caffeine (Hogervorst et al., 2008), creatine (Cook et al., 2011), and ketone supplements (Evans & Egan, 2018) may offset the loss of skills and cognitive performance (e.g., reaction time, decision making) associated with fatigue and/or sleep deprivation. However, this has not been universally tested in cyclists, and more research is therefore required.
Individual responsiveness	• Research and real-life observations both provide evidence of individual responsiveness—both in magnitude and direction—to the effects of performance supplements. • Factors such as gene polymorphisms have been explored as a contributor to individual responsiveness. • For example, the genotype of ADORA2 and CYP1A2 genotypes have been suggested to alter caffeine metabolism and sensitivity, and therefore the impact of caffeine on cycling performance (Guest et al., 2018, 2022). However, meta-analyses pooling the literature have concluded that there is insufficient evidence to explain changes in exercise performance based solely on changes in these specific genes, and where differences occur, they are small, inconsistent, or limited to specific exercise scenarios (Barreto et al., 2021, 2024; Grgic et al., 2021).	• Individual responsiveness to the effects of performance supplements is probable and should be explored both in research settings and in case study approaches to individual cyclists. • Researchers and practitioners who carry out such activities should include approaches that confirm individual responsiveness (such as repeating trials) and distinguish it from normal day-to-day variability in performance (Burke, 2017). • Further work regarding genotypes and performance responses to supplement use is encouraged, but at the present time is not sufficiently robust to inform supplement practices in isolation. Other factors should also be considered, including participant expectation bias and habitual practices.

(continued)

Table 4 (continued)

Issue	Context	Recommendations and examples
Effect of training status or caliber, and age	• There is speculation and some evidence that the training status and athletic caliber of an individual may influence the magnitude of their response to some performance supplements. • This may occur because the combined effects of high-level training and genetic endowment have optimized the mechanisms targeted by the supplement, or because elite athletes are already near their genetic ceiling for performance and any further enhancement is too small to detect in conventional studies. • Meta-analyses have found elite athletes benefit less from nitrate (Senefeld et al., 2020). By contrast, meta-analyses have shown that while effect sizes tend to be lower for high-level athletes, both caffeine (Carvalho et al., 2022) and buffering agents (de Oliveira et al., 2022; Peart et al., 2012; Saunders, Elliott-Sale, et al., 2017) can provide worthwhile benefits for performance.	• Any performance benefit is likely to be worthwhile in high-performance cycling, where margins of success are small and hard to detect using conventional research designs. • Individual cyclists should therefore work with their sports science/medicine/coaching teams to trial supplement use in training and lower level competitions to collect personal data on the benefits and/or detrimental outcomes. • Lower level cyclists should undertake a different cost:benefit analysis, which prioritizes factors that may make a more pronounced performance improvement (e.g., training and equipment) rather than relying on performance supplements alone. • Future research on supplement use in cycling should use standard methodology to describe athlete caliber (e.g., the tiering system proposed by McKay et al., 2022) in order to strengthen meta-analysis and allow for stratification by training status.
Young/junior cyclists	• Considerations should be made regarding the age of the cyclist in making decisions around supplement use, with many bodies having ethical and health concerns around the use of supplements by young athletes (Desbrow et al., 2014). • There is also a need to consider the effect of the use of supplements by adolescents who are still experiencing growth, as well as the potential for supplement use to be a gateway to doping (Hurst, 2023).	• The use of performance supplements by junior cyclists is generally discouraged given the potential for major performance gains from training and experience. • Many cycling teams or sporting organizations have their own policies around appropriate ages or competition categories in which supplement use is permitted. Such decisions may be mediated by the capacity of these organizations to provide a sound environment for evidence-based supplement use.
Female cyclists	• Female participants are underrepresented in sports science/nutrition research. • A specific audit of the literature which informs the use of the performance supplements reported that within 1,826 studies totaling 34,889 participants, just 23% of participants were women. Across different supplements, 0%–8% of studies investigated women exclusively, while fewer (0%–2%) were specifically designed to compare sex-based responses (Smith, McKay, Kuikman, et al., 2022). • Furthermore, only 14% of studies including women attempted to define menstrual status, with only three studies (~0.5%) implementing best practice methodologies to assess menstrual status (Smith, McKay, Kuikman, et al., 2022).	• New research should target the efficacy of performance supplements in female cyclists, and future sports nutrition recommendations should specifically consider how well female cyclists have contributed to the evidence base. Case studies on female athletes are also encouraged. • Future studies should carefully standardize or investigate menstrual status and phase (Elliott-Sale et al., 2021) unless it can be shown that they do not affect the outcome of supplement interventions. • Special consideration should be given to the effect of differences in size, biological sex, and within-athlete differences in reproductive hormones, as well as differences in background nutritional status on performance responses to supplements (Smith, McKay, Ackerman, et al., 2022). • Some reviews have specifically concluded that performance supplements can provide benefits to female athletes when used appropriately (Carr et al., 2023).

Note. TBI = traumatic brain injury.

Although consumers may consider supplements as “natural” or regulated by government codes, in most countries, regulation is less stringent than that applied to food or pharmaceutical products and mostly occurs as postmarketing checks by agencies that are under-resourced for this task (Dwyer et al., 2018; Kozuharov et al., 2022). As outlined earlier in this review, even evidence-based products may cause side effects with their use in some individuals. Although these may be minor in expression (e.g., gastrointestinal

discomfort, difficulty sleeping), this can negatively impact race outcomes and recovery. Furthermore, information from regulatory bodies, consumer complaints made to manufacturers, and hospital reports provides evidence of widespread and larger adverse effects that may arise from supplement use. Surveillance data from 63 hospitals in the United States between 2004 and 2013 estimated that there were 23,005 visits to the emergency department and 2,154 hospital admissions attributed to dietary supplements (Geller

Table 5 Pros and Cons of the Use of Sports Foods and Supplements by Cyclists

Pros of the use of sports foods and supplements (when used in evidence-based protocols and appropriate scenarios)	Issue	Examples
Provides key energy/macronutrients/compounds in amounts that are easily identified and convenient to integrate into the cyclist's eating plan and lifestyle	Provides key energy and macronutrients in a form that can be easily consumed while riding	Sports gels or sports drinks provide a known amount of carbohydrate within a sachet or bidon, allowing a race fueling plan to be quickly calculated. Caffeinated sports gels or caffeinated gums may provide a known dose of caffeine in contrast to the variable caffeine content of coffee (Desbrow et al., 2007). Tinned protein powder or UHT-treated tetra packs of protein drink can be taken to a remote training/race location or on travel, achieving protein targets without the need for constant refrigeration or special food preparation facilities.
	Provides key energy/nutrients/technology advances that enhance gastrointestinal processes beyond that achieved with normal dietary sources, optimizing muscle delivery and reducing gastrointestinal discomfort	Sports bars or gels can be easily carried in the pockets of a cycling jersey; many wrappers or sachets are now manufactured to allow ease of access and consumption of the contents.
	Provides micronutrients/food components in amounts that cannot be consumed in food form (or the foods included in some restricted diets), allowing requirements or therapeutic doses to be achieved to prevent or treat deficiencies	Multiple transportable CHO blends can increase total intestinal CHO uptake and muscle oxidation (Jeukendrup, 2010). In some circumstances, CHO in hydrogel form may also enhance gut transit time via increased gastric emptying to increase rates of exogenous CHO oxidation (Rowe et al., 2022).
	Provides a compound proven to achieve an ergogenic or health promoting benefit	Iron supplements provide doses well in excess of Dietary Reference Intakes and food sources to allow rapid repletion or prevention of inadequate iron stores (McCormick et al., 2020). Creatine supplements provide an exogenous source of creatine that is otherwise not found in a vegan diet, to address the reduced muscle content of cyclists eating a solely plant-based diet (Kaviani et al., 2020).
		Effective doses of evidence-based performance aids such as caffeine, creatine, sodium bicarbonate, BA or nitrate can be provided in supplement form to achieve a supplementation protocol proven to achieve a performance benefit for cycling as outlined in this review. Other supplements may be used to achieve protocols aimed at reducing or managing illness and injury (Maughan et al., 2018).

(continued)

Table 5 (continued)

Issue	Examples
Cons of using sports foods and supplements	Per gram of CHO, a sports gel is more expensive than a banana, while the cost of specialized hydrogels is even greater.
Bespoke and specialized sports foods are more expensive than the “everyday” foods they replace, with the increased price being attributed to the niche market, processing/packaging costs, costs per individual unit, advertising cost, and market “acceptance.” Sports foods are typically not fortified with micronutrients, and even fortified products do not provide the same array of food compounds or the food matrix of everyday foods. As such, overuse of these foods may reduce the overall nutrient density and attributes of whole foods, as well as contribute to other health issues.	Protein powders do not typically contain the calcium and vitamin content of milk and other dairy products. Sports gels and sports confectionery contain minimal amounts of micronutrients, polyphenols, fiber, or other compounds found in fruit. Given sports foods such as drinks, gels, and confectionery are ideally consumed at regular intervals during prolonged training or cycling sessions, there is concern that the sugary and/or acidic nature of these increases the risk of dental caries and poor overall dental health (Schulze & Busse, 2024). The risk is exacerbated by other factors such as changes in salivary characteristics due to prolonged exercise. Therefore, cyclists should be aware of a range of strategies that can mitigate these effects on oral health (Schulze & Busse, 2024).
Supplement use may be seen as a short cut to performance at the expense of evidence-based practices (sound eating practices, adequate sleep, mental preparation, training, etc.), and on the advice of nonexperts.	Studies of athletes have reported mixed rationale for the use of supplements, with information often coming from the internet, coaches, trainers, family/friends, and other athletes rather than sports nutrition experts (Garthe & Maughan, 2018).
The claims made for the majority of products marketed to cyclists are not supported by credible science—i.e., they may not “work.” In most circumstances, even products that are considered evidence-based have not been specifically studied in elite cyclists using protocols that are ecologically valid.	The majority of performance and health supplements belong in Group C (evidence not supportive of benefit among athletes) of the AIS Sports Supplement Framework; Group A (evidence-based) and Group B (emerging interest) contain a relatively smaller number of the products (The AIS Sports Supplement Framework, 2025).
Some sports foods and supplements do not provide an effective dose of an evidence-based product or the dose indicated on the label.	Cyclists may not realize that the labeled amount of BA or creatine contained in some preworkout supplements is below the effective dose for loading (Jagim et al., 2019). Studies of actual contents of supplements often find that some fail to contain the stated doses of ingredients (Kleiner et al., 2015; LeBlanc et al., 2013). This may also occur in some sports foods; a recent study reported that one sports gel brand contained less than 50% of its stated CHO content (Tiller et al., 2025).
Sports foods and supplements may contain harmful ingredients and contaminants not stated on the label.	Many sports supplements have been found to contain undeclared stimulants, unregistered pharmaceutical products, and hormones (Kozuharov et al., 2022). Protein supplements have been found to contain high levels of heavy metals, particularly lead and cadmium (Protein Study 2.0, 2025).
Sports foods and supplements may contain substances that are banned in sport, either as undeclared ingredients or contaminants, or described with confusing names. The use of such products may lead to an ADRV in high-performance athletes who compete under the Anti-Doping Code.	Numerous studies have reported the presence of banned substances in supplements, with a 2022 review summarizing that across 50 studies that tested different types of supplements, 28% of the >3,000 products were found to contain undeclared substances that place the athlete at risk of an ADRV by unintentional doping (Kozuharov et al., 2022).

Note. ADRV = Anti-Doping Rule Violation; CHO = carbohydrate; BA = beta-alanine; UHT-treated = ultra-high temperature treated.

et al., 2015), particularly those associated with muscle building (e.g., protein supplements, etc.), weight loss, and energy production (Geller et al., 2015; Timbo et al., 2018). These products are likely to contain problematic compounds or problematic amounts of stimulants and anabolic-androgenic agents and are not recommended for use by athletes.

Some substances included on the International Standard Prohibited List within the World Anti-Doping Code (World Anti-Doping Code International Standard Prohibited List, 2025) are found in supplements. Such compounds may be included in products that are illegally or legally manufactured and sold as supplements and are available globally via the internet. Sports education programs highlight the need for high-performance athletes to read the labels of sports foods and supplements to avoid such products and the risk of an anti-doping rule violation (ADRV). However, some athletes may fail this task due to their perception that supplements are “natural” or their inability to recognize the different chemical and street names used to describe various prohibited substances on product labels. Moreover, the presence of banned substances as an undeclared ingredient in supplements can also lead to their inadvertent intake. In most cases, this reflects contamination of the supplement and can occur from the use of adulterated raw ingredients or from cross-contamination during the manufacturing process. However, this may not always be an accidental outcome. Some supplements have been found to contain therapeutic doses of steroid compounds, suggesting a deliberate strategy by the manufacturer to gain “street popularity” driven by testimonials of favorable results attributed to the product’s use (Geyer et al., 2008; Judkins & Prock, 2012).

Awareness of the problem emerged in the late 1990s with frequent reports of ADRV in athletes who claimed no use of drugs but admitted to the use of supplements that appeared “safe” to use. An analysis of 634 supplements purchased from 215 different suppliers across 13 different countries in 2000–2001 was the first to confirm the issue of contamination (Geyer et al., 2004). Ninety-four samples (15%) contained undeclared prohormones of nandrolone and testosterone, and another 10% could not be analyzed due to technical difficulties. Since that time, numerous analytical surveys of commercially available supplements have reported contamination or unlabeled presence of banned substances (Ayotte et al., 2001; Baume et al., 2006; Kamber et al., 2001; Lee et al., 2020). A 2022 review that summarized the findings of 50 analytical surveys of supplements found that an average of 28% of products contained undeclared ingredients that could lead to an ADRV (Kozhuharov et al., 2022), with other work suggesting the prevalence of anabolic agents or other prohibited substances ranged from 14% to 50% of samples tested (Jagim et al., 2023). Unfortunately, there is currently no evidence that the problem is improving due to increased understanding or vigilance; a 2025 study from Australia reported that 35% of the 200 products purchased contained WADA Prohibited Substances, despite having greater regulation of therapeutic goods than many other countries (Barker et al., 2025). The majority of the prohibited substances detected were stimulants found in preworkout, “fat burners,” and muscle gain products (Barker et al., 2025).

Although a cyclist may accidentally consume these agents if they are contained as nondeclared ingredients in a supplement, the WADA Strict Liability rule records an Adverse Analytical Finding against the individual, leading to a ban from their sport and overturning of race results. WADA reports from 2013 to 2017 indicate that of 8,287 Adverse Analytical Findings issued across all sports, 58.8% resulted in an ADRV (Aguilar-Navarro et al., 2021). Strategies to mitigate the outcome by providing evidence of

supplement contamination may lead to a reduced sanction, but the ADRV remains and is likely to cause loss of credibility and marketability as well as personal distress. Indeed, considerable resources are required to provide such evidence and require access to both samples of supplements from the original container as well as unopened containers from the same batch/lot number. A substantial number of high-performance athletes, including cyclists, have experienced an ADRV that they attributed to supplement use, with varying outcomes (e.g., see Clarke, 2016; Jones, 2022). Critically, anti-doping rules apply to cyclists of all competitive levels, including amateurs. This explains the priority placed by sporting organizations and anti-doping authorities on education about the safe use of supplements.

There are several strategies that can reduce, but not eliminate, the doping risks associated with supplement use. These include using only products whose specific batches have been certified by Third-Party testing programs (e.g., HFL, HASTA, NSF, and Informed Sport/LGC). Resources such as those produced by Global DRO (<https://www.globaldro.com/Home>), NSF Certified for Sport (<https://www.nsforsport.com/>), the Sports Integrity Australia app (<https://www.sportintegrity.gov.au/resources/sport-integrity-apps-and-vr>), and the Cologne List (<https://www.koelnerliste.com/en/product-database>) provide records of these specific products and batches. These programs do not completely eliminate the risk of an ADRV arising from supplement use as testing of a batch may not detect contamination that is irregularly spread, and third-party auditing programs may not test for all prohibited substances. Avoiding riskier categories of supplements, such as multi-ingredient “fat burners,” “pre-workout,” and “mass gainer” products, and only using products which have a strong evidence base may also assist. Importantly, the key message of anti-doping education programs is that the athlete is responsible for the risks associated with supplement use.

Conclusion

This review describes the rationale and application of sports foods and selected evidence-based performance supplements that are relevant for cycling. We have also highlighted concerns about supplement use, including the expense, the risk of adverse effects, and the risk of an ADRV if the product contains undeclared banned substances. Each cyclist is recommended to work closely with his/her support team or professionals (sports physicians and sports dietitians) to make balanced decisions regarding supplement use.

Acknowledgment

Author Contributions: All authors contributed to the writing of the original draft and reviewed and approved the final manuscript.

References

- Aguilar-Navarro, M., Baltazar-Martins, G., Salinero, J.J., Muñoz-Guerra, J., Plata, M.D.M., Lara, B., & Del Coso, J. (2021). Outcomes of adverse analytical findings in individual and team sports. *Bioanalysis*, 13(1), 5–11. <https://doi.org/10.4155/bio-2020-0263>
- Anderson, M.J., Cotter, J.D., Garnham, A.P., Casley, D.J., & Febbraio, M.A. (2001). Effect of glycerol-induced hyperhydration on thermoregulation and metabolism during exercise in heat. *International Journal of Sport Nutrition and Exercise Metabolism*, 11(3), 315–333. <https://doi.org/10.1123/ijsnem.11.3.315>

- Antonio, J., Candow, D.G., Forbes, S.C., Gualano, B., Jagim, A.R., Kreider, R.B., Rawson, E.S., Smith-Ryan, A.E., VanDusseldorp, T.A., Willoughby, D.S., & Ziegenfuss, T.N. (2021). Common questions and misconceptions about creatine supplementation: What does the scientific evidence really show? *Journal of the International Society of Sports Nutrition*, 18(1), 13. <https://doi.org/10.1186/s12970-021-00412-w>
- Arazi, H., Eghbali, E., & Suzuki, K. (2021). Creatine supplementation, physical exercise and oxidative stress markers: A review of the mechanisms and effectiveness. *Nutrients*, 13(3), 869. <https://doi.org/10.3390/nu13030869>
- Ayotte, C., Lévesque, J.F., Clé Roux, M., Lajeunesse, A., Goudreault, D., & Fakirian, A. (2001). Sport nutritional supplements: Quality and doping controls. *Canadian Journal of Applied Physiology*, 26-(Suppl.), S120–S129. <https://doi.org/10.1139/h2001-047>
- Bailey, S.J., Fulford, J., Vanhatalo, A., Winyard, P.G., Blackwell, J.R., DiMenna, F.J., Wilkerson, D.P., Benjamin, N., & Jones, A.M. (2010). Dietary nitrate supplementation enhances muscle contractile efficiency during knee-extensor exercise in humans. *Journal of Applied Physiology*, 109(1), 135–148. <https://doi.org/10.1152/jappphysiol.00046.2010>
- Bailey, S.J., Winyard, P., Vanhatalo, A., Blackwell, J.R., Dimenna, F.J., Wilkerson, D.P., Tarr, J., Benjamin, N., & Jones, A.M. (2009). Dietary nitrate supplementation reduces the O₂ cost of low-intensity exercise and enhances tolerance to high-intensity exercise in humans. *Journal of Applied Physiology*, 107(4), 1144–1155. <https://doi.org/10.1152/jappphysiol.00722.2009>
- Balsom, P.D., Ekblom, B., Sörerlund, K., Sjödin, B., & Hultman, E. (1993). Creatine supplementation and dynamic high-intensity intermittent exercise. *Scandinavian Journal of Medicine & Science in Sports*, 3(3), 143–149. <https://doi.org/10.1111/j.1600-0838.1993.tb00378.x>
- Baltazar-Martins, G., Brito de Souza, D., Aguilar-Navarro, M., Muñoz-Guerra, J., Plata, M.D.M., & Del Coso, J. (2019). Prevalence and patterns of dietary supplement use in elite Spanish athletes. *Journal of the International Society of Sports Nutrition*, 16(1), 30. <https://doi.org/10.1186/s12970-019-0296-5>
- Barker, L., Cawley, A., Speers, N., Knowler, K., & Chilman, K. (2025). Sports Supplement Analysis Survey for the Prevalence of WADA Prohibited Substances in the Australian Online Marketplace. *Drug Testing and Analysis*, 17(10), 1857–1864. <https://doi.org/10.1002/dta.3893>
- Barreto, G., Esteves, G.P., Marticorena, F., Oliveira, T.N., Grgic, J., & Saunders, B. (2024). Caffeine, CYP1A2 genotype, and exercise performance: A systematic review and meta-analysis. *Medicine & Science in Sports & Exercise*, 56(2), 328–339. <https://doi.org/10.1249/MSS.0000000000003313>
- Barreto, G., Grecco, B., Merola, P., Reis, C.E.G., Gualano, B., & Saunders, B. (2021). Novel insights on caffeine supplementation, CYP1A2 genotype, physiological responses and exercise performance. *European Journal of Applied Physiology*, 121(3), 749–769. <https://doi.org/10.1007/s00421-020-04571-7>
- Baume, N., Mahler, N., Kamber, M., Mangin, P., & Saugy, M. (2006). Research of stimulants and anabolic steroids in dietary supplements. *Scandinavian Journal of Medicine & Science in Sports*, 16(1), 41–48. <https://doi.org/10.1111/j.1600-0838.2005.00442.x>
- Beedie, C.J., Stuart, E.M., Coleman, D.A., & Foad, A.J. (2006). Placebo effects of caffeine on cycling performance. *Medicine & Science in Sports & Exercise*, 38(12), 2159–2164. <https://doi.org/10.1249/01.mss.0000233805.56315.a9>
- Bell, D.G., & McLellan, T.M. (2002). Exercise endurance 1, 3, and 6 h after caffeine ingestion in caffeine users and nonusers. *Journal of Applied Physiology*, 93(4), 1227–1234. <https://doi.org/10.1152/jappphysiol.00187.2002>
- Bellinger, P. (2019). Does ketone ester supplementation really blunt overreaching symptoms during endurance training overload? *The Journal of Physiology*, 597(21), 5307–5308. <https://doi.org/10.1113/JP278830>
- Bellinger, P.M., Howe, S.T., Shing, C.M., & Fell, J.W. (2012). Effect of combined β -alanine and sodium bicarbonate supplementation on cycling performance. *Medicine & Science in Sports & Exercise*, 44(8), 1545. <https://doi.org/10.1249/MSS.0b013e31824cc08d>
- Bellinger, P.M., & Minahan, C.L. (2016). Metabolic consequences of β -alanine supplementation during exhaustive supramaximal cycling and 4000-m time-trial performance. *Applied Physiology, Nutrition, and Metabolism*, 41(8), 864–871. <https://doi.org/10.1139/apnm-2016-0095>
- Birch, R., Noble, D., & Greenhaff, P.L. (1994). The influence of dietary creatine supplementation on performance during repeated bouts of maximal isokinetic cycling in man. *European Journal of Applied Physiology and Occupational Physiology*, 69(3), 268–270. <https://doi.org/10.1007/BF01094800>
- Boldyrev, A.A. (1993). Does carnosine possess direct antioxidant activity? *International Journal of Biochemistry*, 25(8), 1101–1107. [https://doi.org/10.1016/0020-711X\(93\)90587-5](https://doi.org/10.1016/0020-711X(93)90587-5)
- Bone, J.L., Ross, M.L., Tomcik, K.A., Jeacocke, N.A., Hopkins, W.G., & Burke, L.M. (2017). Manipulation of Muscle Creatine and Glycogen Changes Dual X-ray Absorptiometry Estimates of Body Composition. *Medicine & Science in Sports & Exercise*, 49(5), 1029–1035. <https://doi.org/10.1249/MSS.0000000000001174>
- Borchio, L., Machek, S.B., & Machado, M. (2020). Supplemental creatine monohydrate loading improves cognitive function in experienced mountain bikers. *The Journal of Sports Medicine and Physical Fitness*, 60(8), 1168–1170. <https://doi.org/10.23736/S0022-4707.20.10589-9>
- Burke, L.M. (2017). Practical issues in evidence-based use of performance supplements: Supplement interactions, repeated use and individual responses. *Sports Medicine*, 47(S1), 79–100. <https://doi.org/10.1007/s40279-017-0687-1>
- Burke, L.M., Gonzalez, J.T., Areta, J.L., Kuikman, M., Coates, A.M., Bailey, D.M., Moran, J., & Dolan, E. (2025). UCI sports nutrition project: Body composition, energy requirements and energy availability in cycling. [Manuscript submitted for publication].
- Burke, L.M., & Peeling, P. (2018). Methodologies for investigating performance changes with supplement use. *International Journal of Sport Nutrition and Exercise Metabolism*, 28(2), 159–169. <https://doi.org/10.1123/ijnsnem.2017-0325>
- Burke, L.M., & Slater, G.J. (2021). Supplements and sports foods in sports. In *Clinical sports nutrition* (6th ed., pp. 445–477). McGraw Hill Education.
- Burke, L.M., Whitfield, J., & Hawley, J.A. (2025). The race within a race: Together on the marathon starting line but miles apart in the experience. *Free Radical Biology and Medicine*, 227, 367–378. <https://doi.org/10.1016/j.freeradbiomed.2024.10.277>
- Carr, A.J., McKay, A.K.A., Burke, L.M., Smith, E.S., Urwin, C.S., Convit, L., Jardine, W.T., Kelly, M.K., & Saunders, B. (2023). Use of buffers in specific contexts: Highly trained female athletes, extreme environments and combined buffering agents—A narrative review. *Sports Medicine*, 53(Suppl 1), 25–48. <https://doi.org/10.1007/s40279-023-01872-7>
- Carr, A.J., Slater, G.J., Gore, C.J., Dawson, B., & Burke, L.M. (2011). Effect of sodium bicarbonate on [HCO₃⁻], pH, and gastrointestinal symptoms. *International Journal of Sport Nutrition and Exercise Metabolism*, 21(3), 189–194. <https://doi.org/10.1123/ijnsnem.21.3.189>
- Carswell, A.T., Howland, K., Martinez-Gonzalez, B., Baron, P., & Davison, G. (2020). The effect of caffeine on cognitive performance is influenced by CYP1A2 but not ADORA2A genotype, yet neither

- genotype affects exercise performance in healthy adults. *European Journal of Applied Physiology*, 120(7), 1495–1508. <https://doi.org/10.1007/s00421-020-04384-8>
- Carvalho, A., Marticorena, F.M., Grecco, B.H., Barreto, G., & Saunders, B. (2022). Can I have my coffee and drink it? A systematic review and meta-analysis to determine whether habitual caffeine consumption affects the ergogenic effect of caffeine. *Sports Medicine*, 52(9), 2209–2220. <https://doi.org/10.1007/s40279-022-01685-0>
- Casey, A., Constantin-Teodosiu, D., Howell, S., Hultman, E., & Greenhaff, P.L. (1996). Creatine ingestion favorably affects performance and muscle metabolism during maximal exercise in humans. *The American Journal of Physiology*, 271(1 Pt. 1), E31–E37. <https://doi.org/10.1152/ajpendo.1996.271.1.E31>
- Cheuvront, S.N., & Kenefick, R.W. (2014). Dehydration: Physiology, assessment, and performance effects. *Comprehensive Physiology*, 4(1), 257–285. <https://doi.org/10.1002/j.2040-4603.2014.tb00543.x>
- Childs, E., Hohoff, C., Deckert, J., Xu, K., Badner, J., & de Wit, H. (2008). Association between ADORA2A and DRD2 polymorphisms and caffeine-induced anxiety. *Neuropsychopharmacology*, 33(12), 2791–2800. <https://doi.org/10.1038/npp.2008.17>
- Chung, W., Baguet, A., Bex, T., Bishop, D.J., & Derave, W. (2014). Doubling of muscle carnosine concentration does not improve laboratory 1-hr cycling time-trial performance. *International Journal of Sport Nutrition and Exercise Metabolism*, 24(3), 315–324. <https://doi.org/10.1123/ijnsnem.2013-0125>
- Clarke, K., Tchabanenko, K., Pawlosky, R., Carter, E., King, M.T., Musa-Veloso, K., Ho, M., Roberts, A., Robertson, J., VanItallie, T.B., & Veech, R.L. (2012). Kinetics, safety and tolerability of (R)-3-hydroxybutyl (R)-3-hydroxybutyrate in healthy adult subjects. *Regulatory Toxicology and Pharmacology*, 63(3), 401–408. <https://doi.org/10.1016/j.yrtph.2012.04.008>
- Clarke, S. (2016, June 8). Tom Danielson: “I hope to educate others on the dangers of supplement use.” *Cycling Weekly*. <https://www.cyclingweekly.com/news/racing/tom-danielson-i-hope-to-educate-others-on-the-dangers-of-supplement-use-232664>
- Close, G.L., Kasper, A.M., Walsh, N.P., & Maughan, R.J. (2022). “Food first but not always food only”: Recommendations for using dietary supplements in sport. *International Journal of Sport Nutrition and Exercise Metabolism*, 32(5), 371–386. <https://doi.org/10.1123/ijnsnem.2021-0335>
- Coggan, A.R., Leibowitz, J.L., Kadkhodayan, A., Thomas, D.P., Ramamurthy, S., Spearie, C.A., Waller, S., Farmer, M., & Peterson, L.R. (2015). Effect of acute dietary nitrate intake on maximal knee extensor speed and power in healthy men and women. *Nitric Oxide*, 48, 16–21. <https://doi.org/10.1016/j.niox.2014.08.014>
- Coggan, A.R., & Peterson, L.R. (2018). Dietary nitrate enhances the contractile properties of human skeletal muscle. *Exercise and Sport Sciences Reviews*, 46(4), 254–261. <https://doi.org/10.1249/JES.000000000000167>
- Conger, S.A., Tuthill, L.M., & Millard-Stafford, M.L. (2023). Does caffeine increase fat metabolism? A systematic review and meta-analysis. *International Journal of Sport Nutrition and Exercise Metabolism*, 33(2), 112–120. <https://doi.org/10.1123/ijnsnem.2022-0131>
- Cook, C.J., Crewther, B.T., Kilduff, L.P., Drawer, S., & Gaviglio, C.M. (2011). Skill execution and sleep deprivation: Effects of acute caffeine or creatine supplementation—A randomized placebo-controlled trial. *Journal of the International Society of Sports Nutrition*, 8(1), 2. <https://doi.org/10.1186/1550-2783-8-2>
- Cottrell, G.T., Coast, J.R., & Herb, R.A. (2002). Effect of recovery interval on multiple-bout sprint cycling performance after acute creatine supplementation. *Journal of Strength and Conditioning Research*, 16(1), 109–116.
- Cox, G.R., Desbrow, B., Montgomery, P.G., Anderson, M.E., Bruce, C.R., Macrides, T.A., Martin, D.T., Moquin, A., Roberts, A., Hawley, J.A., & Burke, L.M. (2002). Effect of different protocols of caffeine intake on metabolism and endurance performance. *Journal of Applied Physiology*, 93(3), 990–999. <https://doi.org/10.1152/japplphysiol.00249.2002>
- Cox, P.J., Kirk, T., Ashmore, T., Willerton, K., Evans, R., Smith, A., Murray, A.J., Stubbs, B., West, J., McLure, S.W., King, M.T., Dodd, M.S., Holloway, C., Neubauer, S., Drawer, S., Veech, R.L., Griffin, J.L., & Clarke, K. (2016). Nutritional ketosis alters fuel preference and thereby endurance performance in athletes. *Cell Metabolism*, 24(2), 256–268. <https://doi.org/10.1016/j.cmet.2016.07.010>
- Dalle, S., Koppo, K., & Hespel, P. (2021). Sodium bicarbonate improves sprint performance in endurance cycling. *Journal of Science and Medicine in Sport*, 24(3), 301–306. <https://doi.org/10.1016/j.jsams.2020.09.011>
- de Oliveira, L.F., Dolan, E., Swinton, P.A., Durkalec-Michalski, K., Artioli, G.G., McNaughton, L.R., & Saunders, B. (2022). Extracellular buffering supplements to improve exercise capacity and performance: A comprehensive systematic review and meta-analysis. *Sports Medicine*, 52(3), 505–526. <https://doi.org/10.1007/s40279-021-01575-x>
- de Oliveira, L.F., Saunders, B., Yamaguchi, G., Swinton, P., & Giannini Artioli, G. (2020). Is individualization of sodium bicarbonate ingestion based on time to peak necessary? *Medicine & Science in Sports & Exercise*, 52(8), 1801–1808. <https://doi.org/10.1249/MSS.00000000000002313>
- de Salles Painelli, V., Saunders, B., Sale, C., Harris, R.C., Solis, M.Y., Roschel, H., Gualano, B., Artioli, G.G., & Lancha, A.H. (2014). Influence of training status on high-intensity intermittent performance in response to β -alanine supplementation. *Amino Acids*, 46(5), 1207–1215. <https://doi.org/10.1007/s00726-014-1678-2>
- de Souza, J.G., Del Coso, J., Fonseca, F.S., Silva, B.V.C., de Souza, D.B., da Silva Gianoni, R.L., Filip-Stachnik, A., Serrão, J.C., & Claudino, J.G. (2022). Risk or benefit? Side effects of caffeine supplementation in sport: A systematic review. *European Journal of Nutrition*, 61(8), 3823–3834. <https://doi.org/10.1007/s00394-022-02874-3>
- Dearlove, D.J., Faull, O.K., Rolls, E., Clarke, K., & Cox, P.J. (2019). Nutritional ketoacidosis during incremental exercise in healthy athletes. *Frontiers in Physiology*, 10, 290. <https://doi.org/10.3389/fphys.2019.00290>
- Dearlove, D.J., Harrison, O.K., Hodson, L., Jefferson, A., Clarke, K., & Cox, P.J. (2021). The effect of blood ketone concentration and exercise intensity on exogenous ketone oxidation rates in athletes. *Medicine & Science in Sports & Exercise*, 53(3), 505–516. <https://doi.org/10.1249/MSS.0000000000002502>
- Debruyne, F. (2024, November 8). *THE MPCC, « ACTIVE IN THE FIGHT AGAINST DOPING »—MPCC - Mouvement Pour un Cyclisme Crédible*. <https://www.mpcc.fr/en/the-mpcc-active-in-the-fight-against-doping/>
- Derave, W., Ozdemir, M.S., Harris, R.C., Pottier, A., Reyngoudt, H., Koppo, K., Wise, J.A., Achten, E., Özdemir, M.S., Harris, R.C., Pottier, A., Reyngoudt, H., Koppo, K., Wise, J.A., & Achten, E. (2007). β -Alanine supplementation augments muscle carnosine content and attenuates fatigue during repeated isokinetic contraction bouts in trained sprinters. *Journal of Applied Physiology*, 103(5), 1736–1743. <https://doi.org/10.1152/japplphysiol.00397.2007>
- Desbrow, B., Hughes, R., Leveritt, M., & Scheelings, P. (2007). An examination of consumer exposure to caffeine from retail coffee outlets. *Food and Chemical Toxicology: An International Journal Published for the British Industrial Biological Research Association*, 45(9), 1588–1592. <https://doi.org/10.1016/j.fct.2007.02.020>
- Desbrow, B., McCormack, J., Burke, L.M., Cox, G.R., Fallon, K., Hislop, M., Logan, R., Marino, N., Sawyer, S.M., Shaw, G., Star, A., Vidgen,

- H., & Leveritt, M. (2014). Sports Dietitians Australia position statement: Sports nutrition for the adolescent athlete. *International Journal of Sport Nutrition and Exercise Metabolism*, 24(5), 570–584. <https://doi.org/10.1123/ijnsnem.2014-0031>
- Dolan, E., Gualano, B., & Rawson, E.S. (2019). Beyond muscle: The effects of creatine supplementation on brain creatine, cognitive processing, and traumatic brain injury. *European Journal of Sport Science*, 19(1), 1–14. <https://doi.org/10.1080/17461391.2018.1500644>
- Dolan, E., Swinton, P.A., Painelli, V.S., Stephens Hemingway, B., Mazzolani, B., Infante Smaira, F., Saunders, B., Artioli, G.G., & Gualano, B. (2019). A systematic risk assessment and meta-analysis on the use of oral β -alanine supplementation. *Advances in Nutrition*, 10(3), 452–463. <https://doi.org/10.1093/advances/nmy115>
- Douroudos, I.I., Fatouros, I.G., Gourgoulis, V., Jamurtas, A.Z., Tsitsios, T., Hatzinikolaou, A., Margonis, K., Mavromatidis, K., & Taxildaris, K. (2006). Dose-related effects of prolonged NaHCO_3 ingestion during high-intensity exercise. *Medicine & Science in Sports & Exercise*, 38(10), 1746–1753. <https://doi.org/10.1249/01.mss.0000230210.60957.67>
- Dwyer, J.T., Coates, P.M., & Smith, M.J. (2018). Dietary supplements: Regulatory challenges and research resources. *Nutrients*, 10(1), 41. <https://doi.org/10.3390/nu10010041>
- Edge, J., Bishop, D., & Goodman, C. (2006). Effects of chronic NaHCO_3 ingestion during interval training on changes to muscle buffer capacity, metabolism, and short-term endurance performance. *Journal of Applied Physiology*, 101(3), 918–925. <https://doi.org/10.1152/japplphysiol.01534.2005>
- Elliott-Sale, K.J., Minahan, C.L., de Jonge, X.A.K.J., Ackerman, K.E., Sipilä, S., Constantini, N.W., Lebrun, C.M., & Hackney, A.C. (2021). Methodological considerations for studies in sport and exercise science with women as participants: A working guide for standards of practice for research on women. *Sports Medicine*, 51(5), 843–861. <https://doi.org/10.1007/s40279-021-01435-8>
- Evans, E., Walhin, J.-P., Hengist, A., Betts, J.A., Dearlove, D.J., & Gonzalez, J.T. (2023). Ketone monoester ingestion increases postexercise serum erythropoietin concentrations in healthy men. *American Journal of Physiology-Endocrinology and Metabolism*, 324(1), E56–E61. <https://doi.org/10.1152/ajpendo.00264.2022>
- Evans, M., & Egan, B. (2018). Intermittent running and cognitive performance after ketone ester ingestion. *Medicine & Science in Sports & Exercise*, 50(11), 2330–2338. <https://doi.org/10.1249/MSS.0000000000001700>
- Evans, M., McClure, T.S., Koutnik, A.P., & Egan, B. (2022). Exogenous ketone supplements in athletic contexts: Past, present, and future. *Sports Medicine*, 52(Suppl. 1), 25–67. <https://doi.org/10.1007/s40279-022-01756-2>
- Evans, M., Patchett, E., Nally, R., Kearns, R., Larney, M., & Egan, B. (2018). Effect of acute ingestion of β -hydroxybutyrate salts on the response to graded exercise in trained cyclists. *European Journal of Sport Science*, 18(3), 376–386. <https://doi.org/10.1080/17461391.2017.1421711>
- Felippe, L.C., Ferreira, G.A., Lears, S.K., Boari, D., Bertuzzi, R., & Lima-Silva, A.E. (2018). Caffeine increases both total work performed above critical power and peripheral fatigue during a 4-km cycling time trial. *Journal of Applied Physiology*, 124(6), 1491–1501. <https://doi.org/10.1152/japplphysiol.00930.2017>
- Foad, A.J., Beedie, C.J., & Coleman, D.A. (2008). Pharmacological and psychological effects of caffeine ingestion in 40-km cycling performance. *Medicine & Science in Sports & Exercise*, 40(1), 158–165. <https://doi.org/10.1249/mss.0b013e3181593e02>
- Forbes, S.C., Candow, D.G., Neto, J.H.F., Kennedy, M.D., Forbes, J.L., Machado, M., Bustillo, E., Gomez-Lopez, J., Zapata, A., & Antonio, J. (2023). Creatine supplementation and endurance performance: Surges and sprints to win the race. *Journal of the International Society of Sports Nutrition*, 20(1), 2204071. <https://doi.org/10.1080/15502783.2023.2204071>
- Gardiner, C., Weakley, J., Burke, L.M., Roach, G.D., Sargent, C., Maniar, N., Townshend, A., & Halson, S.L. (2023). The effect of caffeine on subsequent sleep: A systematic review and meta-analysis. *Sleep Medicine Reviews*, 69, 101764. <https://doi.org/10.1016/j.smrv.2023.101764>
- Gardiner, C.L., Weakley, J., Burke, L.M., Fernandez, F., Johnston, R.D., Leota, J., Russell, S., Munteanu, G., Townshend, A., & Halson, S.L. (2025). Dose and timing effects of caffeine on subsequent sleep: A randomized clinical crossover trial. *Sleep*, 48(4), zsae230. <https://doi.org/10.1093/sleep/zsae230>
- Garthe, I., & Maughan, R.J. (2018). Athletes and supplements: Prevalence and perspectives. *International Journal of Sport Nutrition and Exercise Metabolism*, 28(2), 126–138. <https://doi.org/10.1123/ijnsnem.2017-0429>
- Geller, A.I., Shehab, N., Weidle, N.J., Lovegrove, M.C., Wolpert, B.J., Timbo, B.B., Mozersky, R.P., & Budnitz, D.S. (2015). Emergency Department Visits for Adverse Events Related to Dietary Supplements. *The New England Journal of Medicine*, 373(16), 1531–1540. <https://doi.org/10.1056/NEJMsa1504267>
- Geyer, H., Parr, M.K., Koehler, K., Mareck, U., Schänzer, W., & Thevis, M. (2008). Nutritional supplements cross-contaminated and faked with doping substances. *Journal of Mass Spectrometry*, 43(7), 892–902. <https://doi.org/10.1002/jms.1452>
- Geyer, H., Parr, M.K., Mareck, U., Reinhart, U., Schrader, Y., & Schänzer, W. (2004). Analysis of non-hormonal nutritional supplements for anabolic-androgenic steroids—Results of an international study. *International Journal of Sports Medicine*, 25(2), 124–129. <https://doi.org/10.1055/s-2004-819955>
- Glaister, M., Chopra, K., Pereira De Sena, A.L., Sternbach, C., Morina, L., & Mavrommatis, Y. (2021). Caffeine, exercise physiology, and time-trial performance: No effect of ADORA2A or CYP1A2 genotypes. *Applied Physiology, Nutrition, and Metabolism*, 46(6), 541–551. <https://doi.org/10.1139/apnm-2020-0551>
- Gough, L.A., Deb, S.K., Sparks, S.A., & McNaughton, L.R. (2018). Sodium bicarbonate improves 4 km time trial cycling performance when individualised to time to peak blood bicarbonate in trained male cyclists. *Journal of Sports Sciences*, 36(15), 1705–1712. <https://doi.org/10.1080/02640414.2017.1410875>
- Gough, L.A., & Sparks, S.A. (2024). The effects of a carbohydrate hydrogel system for the delivery of bicarbonate mini-tablets on acid-base buffering and gastrointestinal symptoms in resting well-trained male cyclists. *Sports Medicine—Open*, 10(1), 17. <https://doi.org/10.1186/s40798-024-00684-x>
- Goulet, E.D.B., Aubertin-Leheudre, M., Plante, G.E., & Dionne, I.J. (2007). A meta-analysis of the effects of glycerol-induced hyperhydration on fluid retention and endurance performance. *International Journal of Sport Nutrition and Exercise Metabolism*, 17(4), 391–410. <https://doi.org/10.1123/ijnsnem.17.4.391>
- Goulet, E.D.B., De La Flore, A., Savoie, F.A., & Gosselin, J. (2018). Salt + glycerol-induced hyperhydration enhances fluid retention more than salt- or glycerol-induced hyperhydration. *International Journal of Sport Nutrition and Exercise Metabolism*, 28(3), 246–252. <https://doi.org/10.1123/ijnsnem.2017-0310>
- Govoni, M., Jansson, E.A., Weitzberg, E., & Lundberg, J.O. (2008). The increase in plasma nitrite after a dietary nitrate load is markedly attenuated by an antibacterial mouthwash. *Nitric Oxide*, 19(4), 333–337. <https://doi.org/10.1016/j.niox.2008.08.003>
- Graham, T.E.G.E., Battram, D.S.B.S., Dela, F.D., El-Sohemy, A.E.-S., & Thong, F.S.L. (2008). Does caffeine alter muscle carbohydrate and fat

- metabolism during exercise? *Applied Physiology, Nutrition, and Metabolism*, 33(6), 1311–1318. <https://doi.org/10.1139/H08-129>
- Graham-Paulson, T., Perret, C., & Goosey-Tolfrey, V. (2016). Improvements in cycling but not handcycling 10 km time trial performance in habitual caffeine users. *Nutrients*, 8(7), 393. <https://doi.org/10.3390/nu8070393>
- Greenhaff, P.L., Bodin, K., Soderlund, K., & Hultman, E. (1994). Effect of oral creatine supplementation on skeletal muscle phosphocreatine resynthesis. *The American Journal of Physiology*, 266(5 Pt. 1), E725–730. <https://doi.org/10.1152/ajpendo.1994.266.5.E725>
- Grgic, J. (2018). Caffeine ingestion enhances Wingate performance: A meta-analysis. *European Journal of Sport Science*, 18(2), 219–225. <https://doi.org/10.1080/17461391.2017.1394371>
- Grgic, J., Pickering, C., Del Coso, J., Schoenfeld, B.J., & Mikulic, P. (2021). CYP1A2 genotype and acute ergogenic effects of caffeine intake on exercise performance: A systematic review. *European Journal of Nutrition*, 60(3), 1181–1195. <https://doi.org/10.1007/s00394-020-02427-6>
- Grzegorzewski, J., Bartsch, F., Köller, A., & König, M. (2021). Pharmacokinetics of caffeine: A systematic analysis of reported data for application in metabolic phenotyping and liver function testing. *Frontiers in Pharmacology*, 12, 752826. <https://doi.org/10.3389/fphar.2021.752826>
- Guest, N., Corey, P., Vescovi, J., & El-Sohemy, A. (2018). Caffeine, CYP1A2 genotype, and endurance performance in athletes. *Medicine & Science in Sports & Exercise*, 50(8), 1570–1578. <https://doi.org/10.1249/MSS.0000000000001596>
- Guest, N.S., Corey, P., Tyrrell, P.N., & El-Sohemy, A. (2022). Effect of caffeine on endurance performance in athletes may depend on HTR2A and CYP1A2 genotypes. *Journal of Strength and Conditioning Research*, 36(9), 2486–2492. <https://doi.org/10.1519/JSC.0000000000003665>
- Guest, N.S., VanDusseldorp, T.A., Nelson, M.T., Grgic, J., Schoenfeld, B.J., Jenkins, N.D.M., Arent, S.M., Antonio, J., Stout, J.R., Trexler, E.T., Smith-Ryan, A.E., Goldstein, E.R., Kalman, D.S., & Campbell, B.I. (2021). International society of sports nutrition position stand: Caffeine and exercise performance. *Journal of the International Society of Sports Nutrition*, 18(1), 1. <https://doi.org/10.1186/s12970-020-00383-4>
- Gurton, W.H., King, D.G., Ranchordas, M.K., Siegler, J.C., & Gough, L.A. (2024). Enhancing exercise performance and recovery through sodium bicarbonate supplementation: Introducing the ingestion recovery framework. *European Journal of Applied Physiology*, 124(11), 3175–3190. <https://doi.org/10.1007/s00421-024-05578-0>
- Haakonssen, E., Hogan, K., Stanley, J., O'Bryan, K., & Leckey, J.J. (2025). UCI sports nutrition project: Competition and training demands, physical characteristics, and nutritional strategies for performance in bicycle motocross race. *International Journal of Sport Nutrition and Exercise Metabolism*. Advance online publication. <https://doi.org/10.1123/ijsnem.2025-0087>
- Haider, G., & Folland, J.P. (2014). Nitrate supplementation enhances the contractile properties of human skeletal muscle. *Medicine & Science in Sports & Exercise*, 46(12), 2234–2243. <https://doi.org/10.1249/MSS.0000000000000351>
- Hall, M., & Trojian, T.H. (2013). Creatine supplementation. *Current Sports Medicine Reports*, 12(4), 240–244. <https://doi.org/10.1249/JSR.0b013e31829cdf2>
- Hannaian, S.J., Lov, J., Hawley, S.E., Dargegen, M., Malenda, D., Gritsas, A., Gouspillou, G., Morais, J.A., & Churchward-Venne, T.A. (2024). Acute ingestion of a ketone monoester, whey protein, or their co-ingestion in the overnight postabsorptive state elicit a similar stimulation of myofibrillar protein synthesis rates in young males: A double-blind randomized trial. *The American Journal of Clinical Nutrition*, 119(3), 716–729. <https://doi.org/10.1016/j.ajcnut.2024.01.004>
- Hargreaves, M., & Spriet, L.L. (2020). Skeletal muscle energy metabolism during exercise. *Nature Metabolism*, 2(9), Article 9. <https://doi.org/10.1038/s42255-020-0251-4>
- Harris, R.C., Söderlund, K., & Hultman, E. (1992). Elevation of creatine in resting and exercised muscle of normal subjects by creatine supplementation. *Clinical Science*, 83(3), 367–374. <https://doi.org/10.1042/cs0830367>
- Harris, R.C., Tallon, M.J., Dunnett, M., Boobis, L., Coakley, J., Kim, H.J., Fallowfield, J.L., Hill, C.A., Sale, C., & Wise, J.A. (2006). The absorption of orally supplied β -alanine and its effect on muscle carnosine synthesis in human vastus lateralis. *Amino Acids*, 30(3), 279–289. <https://doi.org/10.1007/s00726-006-0299-9>
- Harty, P.S., Zabriskie, H.A., Stecker, R.A., Currier, B.S., Tinsley, G.M., Surowiec, K., Jagim, A.R., Richmond, S.R., & Kerksick, C.M. (2020). Caffeine timing improves lower-body muscular performance: A randomized trial. *Frontiers in Nutrition*, 7, 585900. <https://doi.org/10.3389/fnut.2020.585900>
- Hill, C.A., Harris, R.C., Kim, H.J., Harris, B.D., Sale, C., Boobis, L.H., Kim, C.K., & Wise, J.A. (2007). Influence of beta-alanine supplementation on skeletal muscle carnosine concentrations and high intensity cycling capacity. *Amino Acids*, 32(2), 225–233. <https://doi.org/10.1007/s00726-006-0364-4>
- Hitchins, S., Martin, D.T., Burke, L., Yates, K., Fallon, K., Hahn, A., & Dobson, G.P. (1999). Glycerol hyperhydration improves cycle time trial performance in hot humid conditions. *European Journal of Applied Physiology and Occupational Physiology*, 80(5), 494–501. <https://doi.org/10.1007/s004210050623>
- Hogervorst, E., Bandelow, S., Schmitt, J., Jentjens, R., Oliveira, M., Allgrove, J., Carter, T., & Gleeson, M. (2008). Caffeine improves physical and cognitive performance during exhaustive exercise. *Medicine & Science in Sports & Exercise*, 40(10), 1841–1851. <https://doi.org/10.1249/MSS.0b013e31817bb8b7>
- Holdsworth, D.A., Cox, P.J., Kirk, T., Stradling, H., Impey, S.G., & Clarke, K. (2017). A ketone ester drink increases postexercise muscle glycogen synthesis in humans. *Medicine & Science in Sports & Exercise*, 49(9), 1789–1795. <https://doi.org/10.1249/MSS.0000000000001292>
- Hord, N.G., Tang, Y., & Bryan, N.S. (2009). Food sources of nitrates and nitrites: The physiologic context for potential health benefits. *American Journal of Clinical Nutrition*, 90(1), 1–10. <https://doi.org/10.3945/ajcn.2008.27131>
- Howe, S.T., Bellinger, P.M., Driller, M.W., Shing, C.M., & Fell, J.W. (2013). The effect of beta-alanine supplementation on isokinetic force and cycling performance in highly trained cyclists. *International Journal of Sport Nutrition and Exercise Metabolism*, 23(6), 562–570. <https://doi.org/10.1123/ijsnem.23.6.562>
- Huang, S.-H.S., Johnson, K., & Pipe, A.L. (2006). The use of dietary supplements and medications by Canadian athletes at the Atlanta and Sydney Olympic Games. *Clinical Journal of Sport Medicine*, 16(1), 27–33. <https://doi.org/10.1097/01.jsm.0000194766.35443.9c>
- Hultman, E., Söderlund, K., Timmons, J.A., Cederblad, G., & Greenhaff, P.L. (1996). Muscle creatine loading in men. *Journal of Applied Physiology*, 81(1), 232–237. <https://doi.org/10.1152/jappl.1996.81.1.232>
- Hurst, P. (2023). Are dietary supplements a gateway to doping? A retrospective survey of athletes' substance use. *Substance Use & Misuse*, 58(3), 365–370. <https://doi.org/10.1080/10826084.2022.2161320>
- Jagim, A.R., Harty, P.S., & Camic, C.L. (2019). Common ingredient profiles of multi-ingredient pre-workout supplements. *Nutrients*, 11(2), 254. <https://doi.org/10.3390/nu11020254>

- Jagim, A.R., Harty, P.S., Erickson, J.L., Tinsley, G.M., Garner, D., & Galpin, A.J. (2023). Prevalence of adulteration in dietary supplements and recommendations for safe supplement practices in sport. *Frontiers in Sports and Active Living*, 5, 1239121. <https://doi.org/10.3389/fspor.2023.1239121>
- Jardine, W.T., Aisbett, B., Kelly, M.K., Burke, L.M., Ross, M.L., Condo, D., Périard, J.D., & Carr, A.J. (2023). The effect of pre-exercise hyperhydration on exercise performance, physiological outcomes and gastrointestinal symptoms: A systematic review. *Sports Medicine*, 53(11), 2111–2134. <https://doi.org/10.1007/s40279-023-01885-2>
- Jeukendrup, A.E. (2010). Carbohydrate and exercise performance: The role of multiple transportable carbohydrates. *Current Opinion in Clinical Nutrition and Metabolic Care*, 13(4), 452–457. <https://doi.org/10.1097/MCO.0b013e3182339de9f>
- Jeukendrup, A.E., Redegeld, M., Martins, G., Whitfield, J., Burke, L.M., Mujika, I., Dolan, E., & Gonzalez, J. (2025). UCI sports nutrition project: Race nutrition for road cycling [Manuscript submitted for publication].
- Jones, A.M., Vanhatalo, A., Seals, D.R., Rossman, M.J., Pikhova, B., & Jonvik, K.L. (2021). Dietary nitrate and nitric oxide metabolism: Mouth, circulation, skeletal muscle, and exercise performance. *Medicine & Science in Sports & Exercise*, 53(2), 280–294. <https://doi.org/10.1249/MSS.00000000000002470>
- Jones, J. (2022, November 21). Moninger set to become another tainted supplement victim. *CyclingNews.Com*. =<https://autobus.cyclingnews.com/news/?id=2002/nov02/nov21news>
- Jonvik, K.L., Nyakayiru, J., van Loon, L.J.C., & Verdijk, L.B. (2015). Can elite athletes benefit from dietary nitrate supplementation? *Journal of Applied Physiology*, 119(6), 759–761. <https://doi.org/10.1152/japphysiol.00232.2015>
- Ju, J.-S., Smith, J.L., Oppelt, P.J., & Fisher, J.S. (2005). Creatine feeding increases GLUT4 expression in rat skeletal muscle. *American Journal of Physiology, Endocrinology and Metabolism*, 288(2), E347–E352. <https://doi.org/10.1152/ajpendo.00238.2004>
- Judkins, C., & Prock, P. (2012). Supplements and inadvertent doping—How big is the risk to athletes. *Medicine and Sport Science*, 59, 143–152. <https://doi.org/10.1159/000341970>
- Kamber, M., Baume, N., Saugy, M., & Rivier, L. (2001). Nutritional supplements as a source for positive doping cases? *International Journal of Sport Nutrition and Exercise Metabolism*, 11(2), 258–263. <https://doi.org/10.1123/ijnsnem.11.2.258>
- Kamimori, G.H., Karyekar, C.S., Otterstetter, R., Cox, D.S., Balkin, T.J., Belenky, G.L., & Eddington, N.D. (2002). The rate of absorption and relative bioavailability of caffeine administered in chewing gum versus capsules to normal healthy volunteers. *International Journal of Pharmaceutics*, 234(1–2), 159–167. [https://doi.org/10.1016/S0378-5173\(01\)00958-9](https://doi.org/10.1016/S0378-5173(01)00958-9)
- Kaviani, M., Shaw, K., & Chilibeck, P.D. (2020). Benefits of creatine supplementation for vegetarians compared to omnivorous athletes: A systematic review. *International Journal of Environmental Research and Public Health*, 17(9), 3041. <https://doi.org/10.3390/ijerph17093041>
- Kleiner, A.C., Cladis, D.P., & Santerre, C.R. (2015). A comparison of actual versus stated label amounts of EPA and DHA in commercial omega-3 dietary supplements in the United States. *Journal of the Science of Food and Agriculture*, 95(6), 1260–1267. <https://doi.org/10.1002/jsfa.6816>
- Korevaar, D.A., Cohen, J.F., & McInnes, M.D.F. (2019). Ketone ester supplementation in endurance athletes: A miracle drink or “spin”? *The Journal of Physiology*, 597(16), 4407–4408. <https://doi.org/10.1113/JP278296>
- Kozuharov, V.R., Ivanov, K., & Ivanova, S. (2022). Dietary supplements as source of unintentional doping. *BioMed Research International*, 2022(1), 8387271. <https://doi.org/10.1155/2022/8387271>
- Kreider, R.B. (2003). Effects of creatine supplementation on performance and training adaptations. *Molecular and Cellular Biochemistry*, 244(1–2), 89–94. <https://doi.org/10.1023/A:1022465203458>
- Lane, S.C., Areta, J.L., Bird, S.R., Coffey, V.G., Burke, L.M., Desbrow, B., Karagounis, L.G., & Hawley, J.A. (2013). Caffeine ingestion and cycling power output in a low or normal muscle glycogen state. *Medicine & Science in Sports & Exercise*, 45(8), 1577–1584. <https://doi.org/10.1249/MSS.0b013e31828af183>
- Lane, S.C., Hawley, J.A., Desbrow, B., Jones, A.M., Blackwell, J.R., Ross, M.L., Zemski, A.J., & Burke, L.M. (2014). Single and combined effects of beetroot juice and caffeine supplementation on cycling time trial performance. *Applied Physiology Nutrition and Metabolism*, 39(9), 1050–1057. <https://doi.org/10.1139/apnm-2013-0336>
- Larsen, F.J., Schiffer, T.A., Borniquel, S., Sahlin, K., Ekblom, B., Lundberg, J.O., & Weitzberg, E. (2011). Dietary inorganic nitrate improves mitochondrial efficiency in humans. *Cell Metabolism*, 13(2), 149–159. <https://doi.org/10.1016/j.cmet.2011.01.004>
- Larsen, F.J., Weitzberg, E., Lundberg, J.O., & Ekblom, B. (2007). Effects of dietary nitrate on oxygen cost during exercise. *Acta Physiologica*, 191(1), 59–66. <https://doi.org/10.1111/j.1748-1716.2007.01713.x>
- Leach, N.K., Hilton, N.P., Tinnion, D., Dobson, B., McNaughton, L.R., & Sparks, S.A. (2023). Sodium bicarbonate ingestion in a fasted state improves 16.1-km cycling time-trial performance. *Medicine & Science in Sports & Exercise*, 55(12), 2299–2307. <https://doi.org/10.1249/MSS.00000000000003263>
- LeBlanc, E.S., Perrin, N., Johnson, J.D., Ballatore, A., & Hillier, T. (2013). Over-the-counter and compounded vitamin D: Is potency what we expect? *JAMA Internal Medicine*, 173(7), 585–586. <https://doi.org/10.1001/jamainternmed.2013.3812>
- Leckey, J.J., Ross, M.L., Quod, M., Hawley, J.A., & Burke, L.M. (2017). Ketone diester ingestion impairs time-trial performance in professional cyclists. *Frontiers in Physiology*, 8, 806. <https://doi.org/10.3389/fphys.2017.00806>
- Lee, J.H., Han, J.H., Min, A.Y., Kim, H., & Shin, D. (2020). Screening for twenty-eight target anabolic-androgenic steroids in protein supplements using QuEChERS extraction followed by liquid chromatography-tandem mass spectrometry. *Food Additives & Contaminants. Part A, Chemistry, Analysis, Control, Exposure & Risk Assessment*, 37(9), 1425–1436. <https://doi.org/10.1080/19440049.2020.1773543>
- Loraschi, A., Galli, N., & Cosentino, M. (2014). Dietary supplement and drug use and doping knowledge and attitudes in Italian young elite cyclists. *Clinical Journal of Sport Medicine*, 24(3), 238–244. <https://doi.org/10.1097/JSM.0000000000000018>
- Loureiro, L.M.R., Dos Santos Neto, E., Molina, G.E., Amato, A.A., Arruda, S.F., Reis, C.E.G., & da Costa, T.H.M. (2021). Coffee increases post-exercise muscle glycogen recovery in endurance athletes: A randomized clinical trial. *Nutrients*, 13(10), 3335. <https://doi.org/10.3390/nu13103335>
- Lundberg, J.O., Weitzberg, E., & Gladwin, M.T. (2008). The nitrate-nitrite-nitric oxide pathway in physiology and therapeutics. *Nature Reviews Drug Discovery*, 7(2), 156–167. <https://doi.org/10.1038/nrd2466>
- Maté-Muñoz, J.L., Lougedo, J.H., Garnacho-Castaño, M.V., Veiga-Herreros, P., Lozano-Estevan, M.D.C., García-Fernández, P., de Jesús, F., Guodemar-Pérez, J., San Juan, A.F., & Domínguez, R. (2018). Effects of β -alanine supplementation during a 5-week strength training program: A randomized, controlled study. *Journal of the International Society of Sports Nutrition*, 15(1), 19. <https://doi.org/10.1186/s12970-018-0224-0>
- Maughan, R.J., Burke, L.M., Dvorak, J., Larson-Meyer, D.E., Peeling, P., Phillips, S.M., Rawson, E.S., Walsh, N.P., Garthe, I., Geyer, H., Meeusen, R., van Loon, L.J.C., Shirreffs, S.M., Spriet, L.L., Stuart,

- M., Vernec, A., Currell, K., Ali, V.M., Budgett, R.G., ... Engebretsen, L. (2018). IOC consensus statement: Dietary supplements and the high-performance athlete. *British Journal of Sports Medicine*, 52(7), 439–455. <https://doi.org/10.1136/bjsports-2018-099027>
- McCarthy, D.G., Bone, J., Fong, M., Pinckaers, P.J.M., Bostad, W., Richards, D.L., van Loon, L.J.C., & Gibala, M.J. (2023). Acute ketone monoester supplementation impairs 20-min time-trial performance in trained cyclists: A randomized, crossover trial. *International Journal of Sport Nutrition and Exercise Metabolism*, 33(4), 181–188. <https://doi.org/10.1123/ijnsnem.2022-0255>
- McCarthy, D.G., Bostad, W., Powley, F.J., Little, J.P., Richards, D.L., & Gibala, M.J. (2021). Increased cardiorespiratory stress during submaximal cycling after ketone monoester ingestion in endurance-trained adults. *Applied Physiology, Nutrition, and Metabolism*, 46(8), 986–993. <https://doi.org/10.1139/apnm-2020-0999>
- McCormick, R., Sim, M., Dawson, B., & Peeling, P. (2020). Refining Treatment Strategies for Iron Deficient Athletes. *Sports Medicine*, 50(12), 2111–2123. <https://doi.org/10.1007/s40279-020-01360-2>
- McCubbin, A.J., & Irwin, C. (2024). The effect of pre-exercise oral hyperhydration on endurance exercise performance, heart rate, and thermoregulation: A meta-analytical review. *Applied Physiology, Nutrition, and Metabolism*, 49(5), 569–583. <https://doi.org/10.1139/apnm-2023-0384>
- McCusker, R.R., Goldberger, B.A., & Cone, E.J. (2003). Caffeine content of specialty coffees. *Journal of Analytical Toxicology*, 27(7), 520–522. <https://doi.org/10.1093/jat/27.7.520>
- McIlvenna, L.C., Mugeridge, D.J., & Whitfield, J. (2020). Exploring the mechanisms by which nitrate supplementation improves skeletal muscle contractile function: One fibre at a time. *Journal of Physiology*, 598(1), 25–27. <https://doi.org/10.1113/JP279118>
- McKay, A.K.A., Stellingwerff, T., Smith, E.S., Martin, D.T., Mujika, I., Goosey-Tolfrey, V.L., Sheppard, J., & Burke, L.M. (2022). Defining training and performance caliber: A participant classification framework. *International Journal of Sports Physiology and Performance*, 17(2), 317–331. <https://doi.org/10.1123/ijssp.2021-0451>
- McMahon, N.F., Leveritt, M.D., & Pavey, T.G. (2017). The effect of dietary nitrate supplementation on endurance exercise performance in healthy adults: A systematic review and meta-analysis. *Sports Medicine*, 47(4), 735–756. <https://doi.org/10.1007/s40279-016-0617-7>
- McNaughton, L., Backx, K., Palmer, G., & Strange, N. (1999). Effects of chronic bicarbonate ingestion on the performance of high-intensity work. *European Journal of Applied Physiology and Occupational Physiology*, 80(4), 333–336. <https://doi.org/10.1007/s004210050600>
- McNaughton, L., & Cedaro, R. (1992). Sodium citrate ingestion and its effects on maximal anaerobic exercise of different durations. *European Journal of Applied Physiology and Occupational Physiology*, 64(1), 36–41. <https://doi.org/10.1007/BF00376437>
- McNaughton, L., Dalton, B., & Palmer, G. (1999). Sodium bicarbonate can be used as an ergogenic aid in high-intensity, competitive cycle ergometry of 1 h duration. *European Journal of Applied Physiology and Occupational Physiology*, 80(1), 64–69. <https://doi.org/10.1007/s004210050559>
- McNaughton, L.R. (1990). Sodium citrate and anaerobic performance: Implications of dosage. *European Journal of Applied Physiology and Occupational Physiology*, 61(5–6), 392–397. <https://doi.org/10.1007/BF00236058>
- McNaughton, L.R. (1992a). Bicarbonate ingestion: Effects of dosage on 60 s cycle ergometry. *Journal of Sports Sciences*, 10(5), 415–423. <https://doi.org/10.1080/02640419208729940>
- McNaughton, L.R. (1992b). Sodium bicarbonate ingestion and its effects on anaerobic exercise of various durations. *Journal of Sports Sciences*, 10(5), 425–435. <https://doi.org/10.1080/02640419208729941>
- McNaughton, L.R., Lovell, R.J., Siegler, J., Midgley, A.W., Moore, L., & Bentley, D.J. (2008). The effects of caffeine ingestion on time trial cycling performance. *International Journal of Sports Physiology and Performance*, 3(2), 157–163. <https://doi.org/10.1123/ijssp.3.2.157>
- McNaughton, L.R., Siegler, J., & Midgley, A. (2008). Ergogenic effects of sodium bicarbonate. *Current Sports Medicine Reports*, 7(4), 230–236. <https://doi.org/10.1249/JSR.0b013e31817ef530>
- Milioni, F., de Poli, R.A.B., Saunders, B., Gualano, B., da Rocha, A.L., Sanchez Ramos da Silva, A., Muller, P.T.G., & Zagatto, A.M. (2019). Effect of β -alanine supplementation during high-intensity interval training on repeated sprint ability performance and neuromuscular fatigue. *Journal of Applied Physiology*, 127(6), 1599–1610. <https://doi.org/10.1152/japplphysiol.00321.2019>
- Moncada, S., & Higgs, A. (1993). The L-arginine-nitric oxide pathway. *New England Journal of Medicine*, 329(27), 2002–2012. <https://doi.org/10.1056/NEJM199312303292706>
- Morris, D.M., Huot, J.R., Jetton, A.M., Collier, S.R., & Utter, A.C. (2015). Acute sodium ingestion before exercise increases voluntary water consumption resulting in preexercise hyperhydration and improvement in exercise performance in the heat. *International Journal of Sport Nutrition and Exercise Metabolism*, 25(5), 456–462. <https://doi.org/10.1123/ijnsnem.2014-0212>
- Mullie, P., & Autier, P. (2019). Type 1 error. *The Journal of Physiology*, 597(17), 4677–4678. <https://doi.org/10.1113/JP278407>
- Muñoz, A., López-Samanes, Á., Aguilar-Navarro, M., Varillas-Delgado, D., Rivilla-García, J., Moreno-Pérez, V., & Del Coso, J. (2020). Effects of CYP1A2 and ADORA2A genotypes on the ergogenic response to caffeine in professional handball players. *Genes*, 11(8), 933. <https://doi.org/10.3390/genes11080933>
- Murray, A.J., Knight, N.S., Cole, M.A., Cochlin, L.E., Carter, E., Tchabanenko, K., Pichulik, T., Gulston, M.K., Atherton, H.J., Schroeder, M.A., Deacon, R.M.J., Kashiwaya, Y., King, M.T., Pawlosky, R., Rawlins, J.N.P., Tyler, D.J., Griffin, J.L., Robertson, J., Veech, R.L., & Clarke, K. (2016). Novel ketone diet enhances physical and cognitive performance. *FASEB Journal*, 30(12), 4021–4032. <https://doi.org/10.1096/fj.201600773R>
- Nehlig, A., Daval, J.L., & Debray, G. (1992). Caffeine and the central nervous system: Mechanisms of action, biochemical, metabolic and psychostimulant effects. *Brain Research. Brain Research Reviews*, 17(2), 139–170. [https://doi.org/10.1016/0165-0173\(92\)90012-B](https://doi.org/10.1016/0165-0173(92)90012-B)
- Nelson, A.G., Day, R., Glickman-Weiss, E.L., Hegsted, M., Kokkonen, J., & Sampson, B. (2000). Creatine supplementation alters the response to a graded cycle ergometer test. *European Journal of Applied Physiology*, 83(1), 89–94. <https://doi.org/10.1007/s004210000244>
- Nelson, M.D., Stuart-Hill, L.A., & Sleivert, G.G. (2008). Hypervolemia and blood alkalinity: Effect on physiological strain in a warm environment. *International Journal of Sports Physiology and Performance*, 3(4), 501–515. <https://doi.org/10.1123/ijssp.3.4.501>
- Ntessalen, M., Procter, N.E.K., Schwarz, K., Loudon, B.L., Minnion, M., Fernandez, B.O., Vassiliou, V.S., Vauzour, D., Madhani, M., Constantin-Teodosiu, D., Horowitz, J.D., Feelisch, M., Dawson, D., Crichton, P.G., & Frenneaux, M.P. (2020). Inorganic nitrate and nitrite supplementation fails to improve skeletal muscle mitochondrial efficiency in mice and humans. *The American Journal of Clinical Nutrition*, 111(1), 79–89. <https://doi.org/10.1093/ajcn/nqz245>
- Nyakayiru, J., Kouw, I.W.K., Cermak, N.M., Senden, J.M., van Loon, L.J.C., & Verdijk, L.B. (2017). Sodium nitrate ingestion increases skeletal muscle nitrate content in humans. *Journal of Applied Physiology*, 123(3), 637–644. <https://doi.org/10.1152/japplphysiol.01036.2016>
- Oosthuysen, T., Muros, J.J., & Zabala, M. (2025). Nutrition for mountain biking and cyclocross. *International Journal of Sport Nutrition and*

- Exercise Metabolism*. Advance online publication. <https://doi.org/10.1123/ijnsnem.2025-0036>
- Paton, C., Costa, V., & Guglielmo, L. (2015). Effects of caffeine chewing gum on race performance and physiology in male and female cyclists. *Journal of Sports Sciences*, 33(10), 1076–1083. <https://doi.org/10.1080/02640414.2014.984752>
- Pawlak-Chaouch, M., Boissière, J., Gamelin, F.X., Cuvelier, G., Berthoin, S., & Aucouturier, J. (2016). Effect of dietary nitrate supplementation on metabolic rate during rest and exercise in human: A systematic review and a meta-analysis. *Nitric Oxide: Biology and Chemistry*, 53, 65–76. <https://doi.org/10.1016/j.niox.2016.01.001>
- Peart, D.J., Siegler, J.C., & Vince, R.V. (2012). Practical recommendations for coaches and athletes: A meta-analysis of sodium bicarbonate use for athletic performance. *Journal of Strength and Conditioning Research*, 26(7), 1975–1983. <https://doi.org/10.1519/JSC.0b013e3182576f3d>
- Pedersen, D.J., Lessard, S.J., Coffey, V.G., Churchley, E.G., Wootton, A.M., Ng, T., Watt, M.J., & Hawley, J.A. (2008). High rates of muscle glycogen resynthesis after exhaustive exercise when carbohydrate is coingested with caffeine. *Journal of Applied Physiology*, 105(1), 7–13. <https://doi.org/10.1152/japplphysiol.01121.2007>
- Peinado, A.B., Holgado, D., Luque-Casado, A., Rojo-Tirado, M.A., Sanabria, D., González, C., Mateo-March, M., Sánchez-Muñoz, C., Calderón, F.J., & Zabala, M. (2019). Effect of induced alkalosis on performance during a field-simulated BMX cycling competition. *Journal of Science and Medicine in Sport*, 22(3), 335–341. <https://doi.org/10.1016/j.jsams.2018.08.010>
- Pérez-Castillo, Í.M., Williams, J.A., López-Chicharro, J., Mihic, N., Rueda, R., Bouzamondo, H., & Horswill, C.A. (2023). Compositional aspects of beverages designed to promote hydration before, during, and after exercise: Concepts revisited. *Nutrients*, 16(1), 17. <https://doi.org/10.3390/nu16010017>
- Pérez-Piñero, S., Ramos-Campo, D.J., López-Román, F.J., Ortolano, R., Torregrosa-García, A., Luque-Rubia, A.J., Ibáñez-Soroa, N., Andreu-Caravaca, L., & Ávila-Gandía, V. (2024). Effect of high-dose β -Alanine supplementation on uphill cycling performance in World Tour cyclists: A randomised controlled trial. *PLoS One*, 19(9), e0309404. <https://doi.org/10.1371/journal.pone.0309404>
- Perim, P., Gobbi, N., Duarte, B., Oliveira, L.F., Costa, L.A.R., Sale, C., Gualano, B., Dolan, E., & Saunders, B. (2022). Beta-alanine did not improve high-intensity performance throughout simulated road cycling. *European Journal of Sport Science*, 22(8), 1240–1249. <https://doi.org/10.1080/17461391.2021.1940304>
- Persky, A.M., Brazeau, G.A., & Hochhaus, G. (2003). Pharmacokinetics of the Dietary Supplement Creatine. *Clinical Pharmacokinetics*, 42(6), 557–574. <https://doi.org/10.2165/00003088-200342060-00005>
- Petrick, H.L., Brunetta, H.S., Pignaneli, C., Nunes, E.A., van Loon, L.J.C., Burr, J.F., & Holloway, G.P. (2020). In vitro ketone-supported mitochondrial respiration is minimal when other substrates are readily available in cardiac and skeletal muscle. *Journal of Physiology*, 598(21), 4869–4885. <https://doi.org/10.1113/JP280032>
- Pickering, C., & Grgic, J. (2021). A time and a place: A framework for caffeine periodization throughout the sporting year. *Nutrition*, 82, 111046. <https://doi.org/10.1016/j.nut.2020.111046>
- Poff, A.M., Koutnik, A.P., & Egan, B. (2020). Nutritional ketosis with ketogenic diets or exogenous ketones: Features, convergence, and divergence. *Current Sports Medicine Reports*, 19(7), 251–259. <https://doi.org/10.1249/JSR.0000000000000732>
- Poffé, C., Ramaekers, M., Bogaerts, S., & Hespel, P. (2020). Exogenous ketosis impacts neither performance nor muscle glycogen breakdown in prolonged endurance exercise. *Journal of Applied Physiology*, 128(6), 1643–1653. <https://doi.org/10.1152/japplphysiol.00092.2020>
- Poffé, C., Ramaekers, M., Bogaerts, S., & Hespel, P. (2021). Bicarbonate unlocks the ergogenic action of ketone monoester intake in endurance exercise. *Medicine & Science in Sports & Exercise*, 53(2), 431–441. <https://doi.org/10.1249/MSS.0000000000002467>
- Poffé, C., Ramaekers, M., Van Thienen, R., & Hespel, P. (2019). Ketone ester supplementation blunts overreaching symptoms during endurance training overload. *Journal of Physiology*, 597(12), 3009–3027. <https://doi.org/10.1113/JP277831>
- Poffé, C., Robberechts, R., Podlogar, T., Kusters, M., Debevec, T., & Hespel, P. (2021). Exogenous ketosis increases blood and muscle oxygenation but not performance during exercise in hypoxia. *American Journal of Physiology. Regulatory, Integrative and Comparative Physiology*, 321(6), R844–R857. <https://doi.org/10.1152/ajpregu.00198.2021>
- Poffé, C., Robberechts, R., Van Thienen, R., & Hespel, P. (2023). Exogenous ketosis elevates circulating erythropoietin and stimulates muscular angiogenesis during endurance training overload. *The Journal of Physiology*, 601(12), 2345–2358. <https://doi.org/10.1113/JP284346>
- Poffé, C., Wyns, F., Ramaekers, M., & Hespel, P. (2021). Exogenous ketosis impairs 30-min time-trial performance independent of bicarbonate supplementation. *Medicine & Science in Sports & Exercise*, 53(5), 1068–1078. <https://doi.org/10.1249/MSS.0000000000002552>
- Porcelli, S., Ramaglia, M., Bellistri, G., Pavei, G., Pugliese, L., Montorsi, M., Rasica, L., & Marzorati, M. (2015). Aerobic fitness affects the exercise performance responses to nitrate supplementation. *Medicine & Science in Sports & Exercise*, 47(8), 1643–1651. <https://doi.org/10.1249/MSS.0000000000000577>
- Potteiger, J.A., Nickel, G.L., Webster, M.J., Haub, M.D., & Palmer, R.J. (1996). Sodium citrate ingestion enhances 30 km cycling performance. *International Journal of Sports Medicine*, 17(1), 7–11. <https://doi.org/10.1055/s-2007-972800>
- Potteiger, J.A., Webster, M.J., Nickel, G.L., Haub, M.D., & Palmer, R.J. (1996). The effects of buffer ingestion on metabolic factors related to distance running performance. *European Journal of Applied Physiology and Occupational Physiology*, 72(4), 365–371. <https://doi.org/10.1007/BF00599698>
- Protein Study 2.0. (2025, January). *Clean Label Project*. <https://cleanlabelproject.org/protein-study-2-0/>
- Puchalska, P., & Crawford, P.A. (2021). Metabolic and signaling roles of ketone bodies in health and disease. *Annual Review of Nutrition*, 41(1), 49–77. <https://doi.org/10.1146/annurev-nutr-111120-111518>
- Ramos-Campo, D.J., López-Román, F.J., Pérez-Piñero, S., Ortolano, R., Abellán-Ruiz, M.S., Molina Pérez de Los Cobos, E., Luque-Rubia, A.J., Van Elslande, D., & Ávila-Gandía, V. (2023). Effects of ketone monoester and bicarbonate co-ingestion on cycling performance in worldtour cyclists. *International Journal of Sport Nutrition and Exercise Metabolism*, 34(1), 1–10. <https://doi.org/10.1123/ijnsnem.2023-0078>
- Reddy, V.S., Shiva, S., Manikantan, S., & Ramakrishna, S. (2024). Pharmacology of caffeine and its effects on the human body. *European Journal of Medicinal Chemistry Reports*, 10, 100138. <https://doi.org/10.1016/j.ejmcr.2024.100138>
- Rijt, W.J., van Hove, J. L. K., Vaz, F.M., Havinga, R., Allersma, D.P., Zijp, T.R., Bedoyan, J.K., Heiner-Fokkema, M.R., Reijngoud, D.-J., Geraghty, M.T., Wanders, R.J.A., Oosterveer, M.H., & Derks, T.G.J. (2021). Enantiomer-specific pharmacokinetics of D,L-3-hydroxybutyrate: Implications for the treatment of multiple acyl-CoA dehydrogenase deficiency. *Journal of Inherited Metabolic Disease*, 44(4), 926. <https://doi.org/10.1002/jimd.12365>
- Robberechts, R., & Poffé, C. (2024). Defining ketone supplementation: The evolving evidence for postexercise ketone supplementation to improve recovery and adaptation to exercise. *American Journal of*

- Physiology-Cell Physiology*, 326(1), C143–C160. <https://doi.org/10.1152/ajpcell.00485.2023>
- Robberechts, R., Poffé, C., & Hespel, P. (2022). Exogenous ketosis suppresses diuresis and atrial natriuretic peptide during exercise. *Journal of Applied Physiology*, 133(2), 449–460. <https://doi.org/10.1152/japphysiol.00061.2022>
- Robinson, T.M., Sewell, D.A., Hultman, E., & Greenhaff, P.L. (1999). Role of submaximal exercise in promoting creatine and glycogen accumulation in human skeletal muscle. *Journal of Applied Physiology*, 87(2), 598–604. <https://doi.org/10.1152/jappl.1999.87.2.598>
- Rocha, P.L.A., Lima, A.L.C., Saunders, B., & Reis, C.E.G. (2022). Development of a caffeine content table for foods, drinks, medications and supplements typically consumed by the Brazilian population. *Nutrients*, 14(20), 4417. <https://doi.org/10.3390/nu14204417>
- Rodger, S., Plews, D., Laursen, P., & Driller, M. (2017). Oral β -hydroxybutyrate salt fails to improve 4-minute cycling performance following submaximal exercise. *J Sci Cycling*, 6(1), 26–31.
- Rowe, J.T., King, R.F.G.J., King, A.J., Morrison, D.J., Preston, T., Wilson, O.J., & O'Hara, J.P. (2022). Glucose and Fructose Hydrogel Enhances Running Performance, Exogenous Carbohydrate Oxidation, and Gastrointestinal Tolerance. *Medicine & Science in Sports & Exercise*, 54(1), 129–140. <https://doi.org/10.1249/MSS.0000000000002764>
- Ryan, E.J., Kim, C.-H., Fickes, E.J., Williamson, M., Muller, M.D., Barkley, J.E., Gunstad, J., & Glickman, E.L. (2013). Caffeine gum and cycling performance: A timing study. *Journal of Strength and Conditioning Research*, 27(1), 259–264. <https://doi.org/10.1519/JSC.0b013e3182541d03>
- Sato, K., Kashiwaya, Y., Keon, C.A., Tsuchiya, N., King, M.T., Radda, G.K., Chance, B., Clarke, K., & Veech, R.L. (1995). Insulin, ketone bodies, and mitochondrial energy transduction. *The FASEB Journal*, 9(8), 651–658. <https://doi.org/10.1096/fasebj.9.8.7768357>
- Saunders, B., de Oliveira, L.F., da Silva, R.P., de Salles Painelli, V., Gonçalves, L.S., Yamaguchi, G., Mutti, T., Maciel, E., Roschel, H., Artioli, G.G., & Gualano, B. (2017). Placebo in sports nutrition: A proof-of-principle study involving caffeine supplementation. *Scandinavian Journal of Medicine & Science in Sports*, 27(11), 1240–1247. <https://doi.org/10.1111/sms.12793>
- Saunders, B., Elliott-Sale, K., Artioli, G.G., Swinton, P.A., Dolan, E., Roschel, H., Sale, C., & Gualano, B. (2017). β -alanine supplementation to improve exercise capacity and performance: A systematic review and meta-analysis. *British Journal of Sports Medicine*, 51(8), 658–669. <https://doi.org/10.1136/bjsports-2016-096396>
- Saunders, B., Franchi, M., de Oliveira, L.F., da Eira Silva, V., da Silva, R.P., de Salles Painelli, V., Costa, L.A.R., Sale, C., Harris, R.C., Roschel, H., Artioli, G.G., & Gualano, B. (2020). 24-Week β -alanine ingestion does not affect muscle taurine or clinical blood parameters in healthy males. *European Journal of Nutrition*, 59(1), 57–65. <https://doi.org/10.1007/s00394-018-1881-0>
- Schulze, A., & Busse, M. (2024). Sports diet and oral health in athletes: A comprehensive review. *Medicina*, 60(2), 319. <https://doi.org/10.3390/medicina60020319>
- Senefeld, J.W., Wiggins, C.C., Regimbal, R.J., Dominelli, P.B., Baker, S.E., & Joyner, M.J. (2020). Ergogenic effect of nitrate supplementation: A systematic review and meta-analysis. *Medicine & Science in Sports & Exercise*, 52(10), 2250–2261. <https://doi.org/10.1249/MSS.0000000000002363>
- Shannon, E.S., Regnier, A., Dobson, B., Yang, X., Sparks, S.A., & McNaughton, L.R. (2024). The effect of sodium bicarbonate mini-tablets ingested in a carbohydrate hydrogel system on 40 km cycling time trial performance and metabolism in trained male cyclists. *European Journal of Applied Physiology*, 124(12), 3671–3682. <https://doi.org/10.1007/s00421-024-05567-3>
- Shannon, O.M., Allen, J.D., Bescos, R., Burke, L., Clifford, T., Easton, C., Gonzalez, J.T., Jones, A.M., Jonvik, K.L., Larsen, F.J., Peeling, P., Pisknova, B., Siervo, M., Vanhatalo, A., McGawley, K., & Porcelli, S. (2022). Dietary inorganic nitrate as an ergogenic aid: An expert consensus derived via the modified delphi technique. *Sports Medicine*, 52(10), 2537–2558. <https://doi.org/10.1007/s40279-022-01701-3>
- Shaw, D.M., Merien, F., Braakhuis, A., Plews, D., Laursen, P., & Dulson, D.K. (2019). The effect of 1,3-butanediol on cycling time-trial performance. *International Journal of Sport Nutrition and Exercise Metabolism*, 29(5), 466–473. <https://doi.org/10.1123/ijnsnem.2018-0284>
- Shivva, V., Cox, P.J., Clarke, K., Veech, R.L., Tucker, I.G., & Duffull, S.B. (2016). The population pharmacokinetics of D- β -hydroxybutyrate following administration of (R)-3-hydroxybutyl (R)-3-hydroxybutyrate. *AAPS Journal*, 18(3), 678–688. <https://doi.org/10.1208/s12248-016-9879-0>
- Siegler, J.C., Carr, A.J., Jardine, W.T., Convit, L., Cross, R., Chapman, D., Burke, L.M., & Ross, M. (2022). The hyperhydration potential of sodium bicarbonate and sodium citrate. *International Journal of Sport Nutrition and Exercise Metabolism*, 32(2), 74–81. <https://doi.org/10.1123/ijnsnem.2021-0179>
- Sims, S.T., Rehrer, N.J., Bell, M.L., & Cotter, J.D. (2007). Preexercise sodium loading aids fluid balance and endurance for women exercising in the heat. *Journal of Applied Physiology*, 103(2), 534–541. <https://doi.org/10.1152/japphysiol.01203.2006>
- Smith, E.S., McKay, A.K.A., Ackerman, K.E., Harris, R., Elliott-Sale, K.J., Stellingwerff, T., & Burke, L.M. (2022). Methodology review: A protocol to audit the representation of female athletes in sports science and sports medicine research. *International Journal of Sport Nutrition and Exercise Metabolism*, 32(2), 114–127. <https://doi.org/10.1123/ijnsnem.2021-0257>
- Smith, E.S., McKay, A.K.A., Kuikman, M., Ackerman, K.E., Harris, R., Elliott-Sale, K.J., Stellingwerff, T., & Burke, L.M. (2022). Auditing the representation of female versus male athletes in sports science and sports medicine research: Evidence-based performance supplements. *Nutrients*, 14(5), 953. <https://doi.org/10.3390/nu14050953>
- Stadheim, H.K., Spencer, M., Olsen, R., & Jensen, J. (2014). Caffeine and performance over consecutive days of simulated competition. *Medicine & Science in Sports & Exercise*, 46(9), 1787–1796. <https://doi.org/10.1249/MSS.0000000000000288>
- Stanley, J., Leo, P., Haakonssen, E., & Leckey, J.J. (2025). UCI sports nutrition project: Performance nutrition for sprint and endurance track cycling. *International Journal of Sport Nutrition and Exercise Metabolism*. Advance online publication. <https://doi.org/10.1123/ijnsnem.2025-0043>
- Stegen, S., Blancquaert, L., Everaert, I., Bex, T., Taes, Y., Calders, P., Achten, E., & Derave, W. (2013). Meal and beta-alanine coingestion enhances muscle carnosine loading. *Medicine & Science in Sports & Exercise*, 45(8), 1478–1485. <https://doi.org/10.1249/MSS.0b013e31828ab073>
- Stellingwerff, T., Anwander, H., Egger, A., Buehler, T., Kreis, R., Decombaz, J., & Boesch, C. (2012). Effect of two β -alanine dosing protocols on muscle carnosine synthesis and washout. *Amino Acids*, 42(6), 2461–2472. <https://doi.org/10.1007/s00726-011-1054-4>
- Stubbs, B.J., Cox, P.J., Evans, R.D., Cyranka, M., Clarke, K., & de Wet, H. (2018). A ketone ester drink lowers human ghrelin and appetite. *Obesity*, 26(2), 269–273. <https://doi.org/10.1002/oby.22051>
- Stubbs, B.J., Cox, P.J., Evans, R.D., Santer, P., Miller, J.J., Faull, O.K., Magor-Elliott, S., Hiyama, S., Stirling, M., & Clarke, K. (2017). On the metabolism of exogenous ketones in humans. *Frontiers in Physiology*, 8, 848. <https://doi.org/10.3389/fphys.2017.00848>
- Stubbs, B.J., Cox, P.J., Kirk, T., Evans, R.D., & Clarke, K. (2019). Gastrointestinal effects of exogenous ketone drinks are infrequent,

- mild, and vary according to ketone compound and dose. *International Journal of Sport Nutrition and Exercise Metabolism*, 29(6), 596–603. <https://doi.org/10.1123/ijnsnem.2019-0014>
- Talanian, J.L., & Spriet, L.L. (2016). Low and moderate doses of caffeine late in exercise improve performance in trained cyclists. *Applied Physiology, Nutrition, and Metabolism*, 41(8), 850–855. <https://doi.org/10.1139/apnm-2016-0053>
- The AIS Sports Supplement Framework. (2025). *The AIS Sports Supplement Framework*. <https://www.ais.gov.au/nutrition/supplements>
- 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. <https://doi.org/10.1249/MSS.0000000000000852>
- Tiller, N.B., Burke, L.M., Howe, S.M., Koop, J., Ohm, J.R., & Burgess, B. (2025). What's (not) in your supplement? An energy and macronutrient analysis of commercially available carbohydrate gels. *International Journal of Sport Nutrition and Exercise Metabolism*, 35(2), 162–170. <https://doi.org/10.1123/ijnsnem.2024-0174>
- Timbo, B.B., Chirtel, S.J., Ihrie, J., Oladipo, T., Velez-Suarez, L., Brewer, V., & Mozersky, R. (2018). Dietary supplement adverse event report data from the FDA Center for Food Safety and Applied Nutrition Adverse Event Reporting System (CAERS), 2004–2013. *The Annals of Pharmacotherapy*, 52(5), 431–438. <https://doi.org/10.1177/1060028017744316>
- Tomazini, F., Santos-Mariano, A.C., Andrade-Souza, V.A., Sebben, V.C., De Maria, C.A.B., Coelho, D.B., Bertuzzi, R., Silva-Cavalcante, M.D., & Lima-Silva, A.E. (2020). Caffeine but not acetaminophen increases 4-km cycling time-trial performance. *PharmaNutrition*, 12, 100181. <https://doi.org/10.1016/j.phanu.2020.100181>
- Tomcik, K.A., Camera, D.M., Bone, J.L., Ross, M.L., Jeacocke, N.A., Tachtsis, B., Senden, J., Van Loon, L.J.C., Hawley, J.A., & Burke, L.M. (2018). Effects of creatine and carbohydrate loading on cycling time trial performance. *Medicine & Science in Sports & Exercise*, 50(1), 141–150. <https://doi.org/10.1249/MSS.000000000000001401>
- Tsai, Y.-C., Chou, Y.-C., Wu, A.-B., Hu, C.-M., Chen, C.-Y., Chen, F.-A., & Lee, J.-A. (2006). Stereoselective effects of 3-hydroxybutyrate on glucose utilization of rat cardiomyocytes. *Life Sciences*, 78(12), 1385–1391. <https://doi.org/10.1016/j.lfs.2005.07.013>
- Urwin, C.S., Snow, R.J., Condo, D., Snipe, R., Wadley, G.D., & Carr, A.J. (2021). Factors influencing blood alkalosis and other physiological responses, gastrointestinal symptoms, and exercise performance following sodium citrate supplementation: A review. *International Journal of Sport Nutrition and Exercise Metabolism*, 31(2), 168–186. <https://doi.org/10.1123/ijnsnem.2020-0192>
- Urwin, C.S., Snow, R.J., Condo, D., Snipe, R.M.J., Wadley, G.D., Convit, L., & Carr, A.J. (2023). A comparison of sodium citrate and sodium bicarbonate ingestion: Blood alkalosis and gastrointestinal symptoms. *International Journal of Sport Nutrition and Exercise Metabolism*, 33(1), 1–10. <https://doi.org/10.1123/ijnsnem.2022-0083>
- Urwin, C.S., Snow, R.J., Orellana, L., Condo, D., Wadley, G.D., & Carr, A.J. (2019). Sodium citrate ingestion protocol impacts induced alkalosis, gastrointestinal symptoms, and palatability. *Physiological Reports*, 7(19), e14216. <https://doi.org/10.14814/phy2.14216>
- Valenzuela, P.L., Leo, P., Mateo-March, M., Gabriele, G., Seiler, S., & Mujika, I. (2025). UCI sports nutrition project: The science of successful cycling performance. *International Journal of Sport Nutrition and Exercise Metabolism*. Advance online publication. <https://doi.org/10.1123/ijnsnem.2025-0157>
- van Loon, L.J.C., Murphy, R., Oosterlaar, A.M., Cameron-Smith, D., Hargreaves, M., Wagenmakers, A.J.M., & Snow, R. (2004). Creatine supplementation increases glycogen storage but not GLUT-4 expression in human skeletal muscle. *Clinical Science*, 106(1), 99–106. <https://doi.org/10.1042/CS20030116>
- van Rosendal, S.P., Osborne, M.A., Fasset, R.G., & Coombes, J.S. (2009). Physiological and performance effects of glycerol hyperhydration and rehydration. *Nutrition Reviews*, 67(12), 690–705. <https://doi.org/10.1111/j.1753-4887.2009.00254.x>
- Van Thienen, R., Van Proeyen, K., Vanden Eynde, B., Puype, J., Lefere, T., & Hespel, P. (2009). Beta-alanine improves sprint performance in endurance cycling. *Medicine & Science in Sports & Exercise*, 41(4), 898–903. <https://doi.org/10.1249/MSS.0b013e31818db708>
- Vandoorne, T., De Smet, S., Ramaekers, M., Van Thienen, R., De Bock, K., Clarke, K., & Hespel, P. (2017). Intake of a ketone ester drink during recovery from exercise promotes mTORC1 signaling but not glycogen resynthesis in human muscle. *Frontiers in Physiology*, 8, 310. <https://doi.org/10.3389/fphys.2017.00310>
- Veech, R.L. (2014). Ketone ester effects on metabolism and transcription. *Journal of Lipid Research*, 55(10), 2004–2006. <https://doi.org/10.1194/jlr.R046292>
- Viinamäki, O. (1990). The effect of hydration status on plasma vasopressin release during physical exercise in man. *Acta Physiologica Scandinavica*, 139(1), 133–137. <https://doi.org/10.1111/j.1748-1716.1990.tb08905.x>
- Volek, J.S., Noakes, T., & Phinney, S.D. (2015). Rethinking fat as a fuel for endurance exercise. *European Journal of Sport Science*, 15(1), 13–20. <https://doi.org/10.1080/17461391.2014.959564>
- Whitfield, J., Gamu, D., Heigenhauser, G.J.F., Van Loon, L.J.C., Spriet, L.L., Tupling, A.R., & Holloway, G.P. (2017). Beetroot juice increases human muscle force without changing Ca²⁺-handling proteins. *Medicine & Science in Sports & Exercise*, 49(10), 2016–2024. <https://doi.org/10.1249/MSS.0000000000001321>
- Whitfield, J., Ludzki, A., Heigenhauser, G.J.F., Senden, J.M.G., Verdijk, L.B., van Loon, L.J.C., Spriet, L.L., & Holloway, G.P. (2016). Beetroot juice supplementation reduces whole body oxygen consumption but does not improve indices of mitochondrial efficiency in human skeletal muscle. *Journal of Physiology*, 594(2), 421–435. <https://doi.org/10.1113/JP270844>
- Whitfield, J., Mujika, I., & Burke, L.M. (2025). UCI sports nutrition project: Nutrition for emerging cycling disciplines of esports and gravel. *International Journal of Sport Nutrition and Exercise Metabolism*. Advance online publication. <https://doi.org/10.1123/ijnsnem.2025-0189>
- Wickham, K.A., McCarthy, D.G., Pereira, J.M., Cervone, D.T., Verdijk, L.B., van Loon, L.J.C., Power, G.A., & Spriet, L.L. (2019). No effect of beetroot juice supplementation on exercise economy and performance in recreationally active females despite increased torque production. *Physiological Reports*, 7(2), e13982. <https://doi.org/10.14814/phy2.13982>
- Wickham, K.A., & Spriet, L.L. (2018). Administration of caffeine in alternate forms. *Sports Medicine*, 48(Suppl. 1), 79–91. <https://doi.org/10.1007/s40279-017-0848-2>
- Wickham, K.A., & Spriet, L.L. (2019). No longer beeting around the bush: A review of potential sex differences with dietary nitrate supplementation. *Applied Physiology, Nutrition, and Metabolism*, 44(9), 915–924. <https://doi.org/10.1139/apnm-2019-0063>
- Wiles, J.D., Coleman, D., Tegerdine, M., & Swaine, I.L. (2006). The effects of caffeine ingestion on performance time, speed and power during a laboratory-based 1 km cycling time-trial. *Journal of Sports Sciences*, 24(11), 1165–1171. <https://doi.org/10.1080/02640410500457687>
- World Anti-Doping Code International Standard Prohibited List. (2025). WADA. https://www.wada-ama.org/sites/default/files/2024-09/2025_list_en_final_clean_12_september_2024.pdf

- Wylie, L.J., Park, J.W., Vanhatalo, A., Kadach, S., Black, M.I., Stoyanov, Z., Schechter, A.N., Jones, A.M., & Pisknová, B. (2019). Human skeletal muscle nitrate store: Influence of dietary nitrate supplementation and exercise. *The Journal of Physiology*, 597(23), 5565–5576. <https://doi.org/10.1113/JP278076>
- Yeo, S.E., Jentjens, R.L.P.G., Wallis, G.A., & Jeukendrup, A.E. (2005). Caffeine increases exogenous carbohydrate oxidation during exercise. *Journal of Applied Physiology*, 99(3), 844–850. <https://doi.org/10.1152/jappphysiol.00170.2005>
- Zart, S., & Fröhlich, M. (2025). Ergogenic effects of supplement combinations on endurance performance: A systematic review and meta-analysis of randomized controlled trials. *Journal of the International Society of Sports Nutrition*, 22(1), 2524033. <https://doi.org/10.1080/15502783.2025.2524033>
- Ziegenfuss, T.N., Lonnie, L.M., & Lemon, P.W.R. (1998). Acute fluid volume changes in men during three days of creatine supplementation. *Journal of Exercise Physiology*, 1(3), 1–9.

Nontechnical Summary

The use of sports foods and supplements has become popular among cyclists across all disciplines in order to meet energy and nutrient targets and to enhance health, performance, and recovery outcomes. This review is part of a series of articles commissioned by Union Cycliste Internationale contributing to the preparation of a consensus statement on nutrition for cycling and will provide an overview of the different types of products most frequently used in cycling, the rationale for their uses, as well as highlighting some caveats, considerations, and contemporary applications of sports foods and supplements. Specifically, we provide a summary of supplements with a strong evidence base based on the Sports Supplement Framework of the Australian Institute

of Sport and the Position Stand of the International Olympic Committee on Dietary Supplements and the High-Performance Athlete including caffeine, creatine, sodium bicarbonate, beta-alanine, dietary nitrate, and glycerol, as well as a key focus on exogenous ketones given the controversy surrounding their use in cycling. We outline the mechanisms of action for these supplements the accepted protocols for their use and timing, and the potential ergogenic effects or side-effects. We also highlight key considerations surrounding the safety and anti-doping risks that sports foods and supplements pose among athletes, delving into the pros and cons for including them as part of an overall nutrition plan.