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Human Kinetics
SCHOLARLY REVIEW

A Systematic Review of CrossFit® Workouts and Dietary and Supplementation Interventions to Guide Nutritional Strategies and Future Research in CrossFit®

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CrossFit® is a high-intensity functional training method consisting of daily workouts called "workouts of the day." No nutritional recommendations exist for CrossFit® that are supported by scientific evidence regarding the energetic demands of this type of activity or dietary and supplement interventions. This systematic review performed in accordance with PRISMA guidelines aimed to identify studies that determined (a) the physiological and metabolic demands of CrossFit® and (b) the effects of nutritional strategies on CrossFit® performance to guide nutritional recommendations for optimal recovery, adaptations, and performance for CrossFit® athletes and direct future research in this emerging area. Three databases were searched for studies that investigated physiological responses to CrossFit® and dietary or supplementation interventions on CrossFit® performance. Various physiological measures revealed the intense nature of all CrossFit® workouts of the day, reflected in substantial muscle fatigue and damage. Dietary and supplementation studies provided an unclear insight into effective strategies to improve performance and enhance adaptations and recovery due to methodological shortcomings across studies. This systematic review showed that CrossFit® is a high-intensity sport with fairly homogenous anaerobic and aerobic characteristics, resulting in substantial metabolic stress, leading to metabolite accumulation (e.g., lactate and hydrogen ions) and increased markers of muscle damage and muscle fatigue. Limited interventional data exist on dietary and supplementation strategies to optimize CrossFit® performance, and most are moderate to very low quality with some critical methodological limitations, precluding solid conclusions on their efficacy. High-quality work is needed to confirm the ideal dietary and supplemental strategies for optimal performance and recovery for CrossFit® athletes and is an exciting avenue for further research.

Keywords: carbohydrate, dietary supplements, high-intensity functional training, nutrition, workout of the day

CrossFit® is one of the fastest growing high-intensity functional training methods in the world, consisting of daily workouts commonly termed "workout of the day" (WODs; Glassman, 2007). These WODs focus on functional movements with numerous variations, implementing a unique blend of gymnastics, weightlifting exercises, and cardiovascular activity. CrossFit® WODs require individuals to perform their exercises with a high level of technique and power adapted to the fitness capacity of the individual (Glassman, 2010). The WODs are always meant to be performed at high intensity and without long periods of recovery between exercises or sets during a training session, leading to situations of overload and fatigue (Bergeron et al., 2011). CrossFit® Benchmarks are WODs that are used periodically to monitor progress throughout an athlete's training cycle (Butcher et al., 2015) by comparing their performance over time (e.g., number of repetitions, time to completion, etc.). These WODs are given female names, such as "Grace," "Fran," and "Cindy," although there are also "Hero WODs" named after American soldiers killed in action (Glassman, 2007). Benchmarks are commonly used in CrossFit® competitions, the largest of which is the annual CrossFit® Games, although the workouts that are adopted vary widely and are continuously updated and reformatted. There is also the CrossFit Open, a yearly online competition wherein practitioners and professionals from around the world perform one workout per week, announced by CrossFit®, over 5 weeks and upload their scores to an official CrossFit® Games leaderboard.

CrossFit® training can lead to beneficial adaptations in aerobic capacity (Barfield & Anderson, 2014; Murawska-Cialowicz et al., 2015) and muscular endurance (Barfield & Anderson, 2014). Nonetheless, CrossFit® could lead to overtraining if not closely

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monitored (Drake et al., 2017), as it can lead to significantly increased muscle soreness, swelling, and fatigue compared with a standard training protocol, according to the American College of Sports Medicine guidelines (Drum et al., 2017). Furthermore, CrossFit® is also associated with considerably high injury rates, such as musculoskeletal, shoulder, and spine injuries (Hak et al., 2013; Hopkins et al., 2019; Weisenthal et al., 2014), although the underlying causes of these injuries are likely multifactorial and could include poor technique, malnutrition, and/or insufficient recovery. In addition, CrossFit® is a form of concurrent training, which may hinder peak adaptations (Coffey & Hawley, 2017). This highlights the need for proper understanding of the physiological and metabolic demands of CrossFit® WODs (e.g., heart rate [HR] response, oxygen uptake, blood lactate [Lac] response, etc.) to optimize gains for improved adaptation, recovery, and, ultimately, performance. In this regard, nutrition plays a pivotal role in maintaining health, supporting training and recovery processes, and enhancing exercise capacity (Moran et al., 2012; Mountjoy et al., 2018; Thomas et al., 2016a). Despite a lack of scientific evidence, Paleo and Zone diets are commonly recommended among CrossFit® trainers (Maxwell et al., 2017), and CrossFit® practitioners appear to engage in extreme dietary practices with a large focus on weight/fat loss (Brescansin et al., 2019), which may be for aesthetic reasons, to improve health, or to enhance performance. Inadequate energy intake has been reported among CrossFit® practitioners (Gogojewicz et al., 2020), suggesting a need for dietary recommendations that are embedded within scientific evidence to guide good practice.

The present study aimed to perform a systematic review of studies involving CrossFit® exercise to determine (a) the physiological and metabolic demands of CrossFit® exercises and (b) the effects of nutritional and supplementation strategies on CrossFit® performance to guide nutritional recommendations for optimal recovery, adaptations, and performance for CrossFit® and direct future research in this emerging area.

Methods

Study Eligibility

This systematic review was performed following the Preferred Reporting Guidelines for Systematic Reviews and Meta-analyses (Moher et al., 2015) with two distinct aims to include studies that investigated (a) physiological and metabolic responses to CrossFit® exercise (e.g., HR, oxygen uptake, [Lac], etc.) and (b) dietary or nutritional interventions on CrossFit® performance. Our research question was framed according to Population, Intervention, Comparator, Outcomes, Study Design (Amir-Behghadami & Janati, 2020). The population included healthy men and women (recreationally active, trained individuals and professional athletes) of any age, but studies conducted with diseased-state participants were not considered. For Part A, the study must have evaluated at least one physiological measure throughout or following CrossFit® exercise. Exercise protocols commonly used in CrossFit® (training and competition) were included, but studies involving only general non-CrossFit®-specific high-intensity functional training protocols were not. For Part B, the nutritional and dietary interventions must have investigated the effect of any acute or chronic dietary or supplementation protocol, in isolation or in combination with training, on CrossFit® performance. In relation to the comparator for the intervention studies, the protocol for this review determined that only controlled studies were included. Only peer-reviewed, original studies on humans that were written in English or Portuguese were included.

Search Strategy

An electronic search of the literature was performed in March 2020 and updated in July 2020 using three databases (PubMed, Web of Science, and SPORTDiscus) to identify relevant articles, and additional articles were identified through website searching, citation tracking, and reference chaining (Figure 1). The search terms "CrossFit" AND ("Nutrition" or "Diet" or "Supplement" or "Supplementation" or "Performance" or "Physiology" or "Metabolism") were included. No year restrictions were applied to the search. Following the removal of duplicates, a two-phase strategy was performed by two independent reviewers (R.A.S. de Souza and A.G. da Silva) using freely available software Rayyan® (Ouzzani et al., 2016). Phase one assessed the eligibility of the title and abstract of every hit generated from the search terms against the inclusion/exclusion criteria. Studies with questionable suitability were included at this stage, and a final decision was reached at the next phase. In phase two, full articles were retrieved and assessed against the eligibility criteria. Reference lists of relevant original and review articles were screened to ensure that all relevant studies were included. Any differences of opinion relating to study eligibility were resolved through discussion or with the help of a third reviewer (B. Saunders).

Data Extraction

Data extraction was performed by two reviewers, one extracting for Part A (A.G. da Silva) and another for Part B (R.A.S. de Souza), and subsequently cross-checked to avoid possible errors. The following information was extracted from the selected studies: author and year of publication, experimental design, population characteristics, intervention protocol (Part B only), exercise protocol, physiological parameters, and exercise-related outcomes (Part B only). The data were extracted using pretrialed standardized spreadsheets.

Quality Assessment

Evaluation of the quality of the studies was performed in a blinded manner by two reviewers (L.K.F. Souza and M.F. de Souza) using an adapted questionnaire (Downs & Black, 1998) for Part A and Part B (see Supplementary Material [available online]). Any disagreements were resolved between reviewers through discussion and, when necessary, with the help of a third reviewer (B. Saunders). For the purpose of this review, we adapted the questions of the checklist to focus on different aspects of the design and conduct of the trials, such as the population employed, randomization process, study control (familiarization, test–retest, validity), deviations from the intended interventions and reporting, and lack of data. These aspects were used as a criterion for a 13-point (Part A) or 16-point (Part B) adapted questionnaire. According to each question, the answers were classified with points from 0 to 2 that were summed to provide an overall score. The quality score was ranked according to the following intervals: high (15–17), moderate (14–12), low (11–9), and very low (≤8) for studies included in Part A and high (18–20), moderate (15–17), low (12–14), and very low (≤11) for intervention studies in Part B. No article in this review was excluded based upon the quality appraisal; however, for subjective discussion of the results, this evaluation was considered.

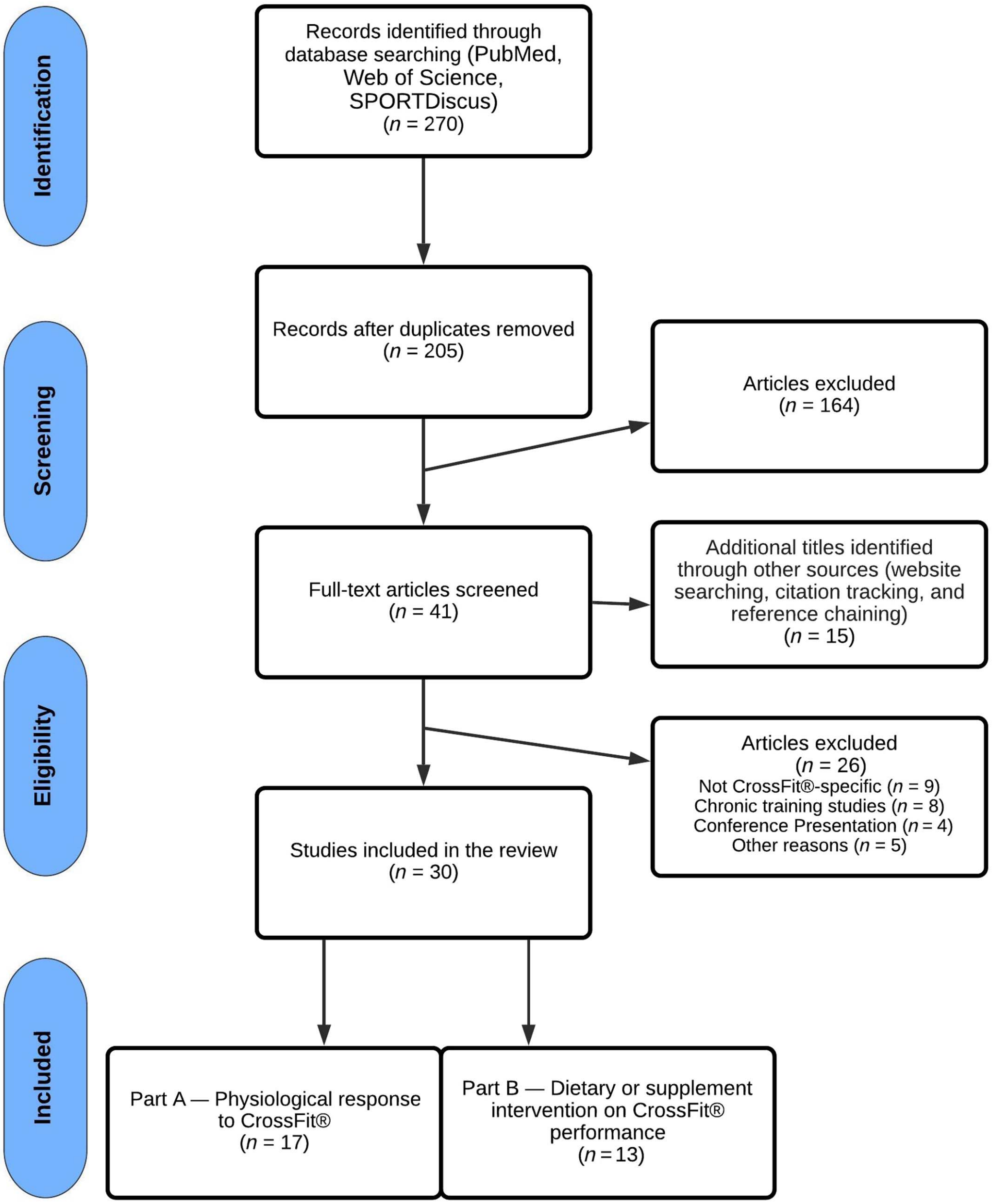

Figure 1 — Flow diagram of the search strategy.

Results

Study Search

The initial search resulted in 270 articles (Figure 1), 205 following the removal of duplicates. Phase one resulted in the exclusion of 164 articles with the remaining 41 articles screened in their entirety for suitability. A further 15 articles were identified from references lists and article chaining, and full texts of these were also screened. A total of 30 articles met the inclusion criteria, seventeen for inclusion in Part A (Tables 1 and 2) and thirteen in Part B (Table 3). Twenty-six articles were written in English with one (in Part B) published in Portuguese.

Part A

Seventeen studies investigated the physiological effects of CrossFit® workouts, including five CrossFit® Benchmark WODs: Rahoi (Escobar et al., 2017), Cindy (Fernández-Fernández et al., 2015; Kliszczewicz et al., 2015; Kliszczewicz et al., 2014; Maté-Muñoz et al., 2017, 2018), Fran (Fernández-Fernández et al., 2015; Tibana et al., 2018a, 2018b), Fight Gone Bad (FGB; Tibana et al., 2018a, 2018b), and Murph (Carreker & Grosicki, 2020; Table 1). Other studies evaluated responses to specific "Open" workouts (Coco et al., 2019; Moreira et al., 2019; Perciavalle et al., 2016) or other commonly used training WODs (Cronin et al., 2016; Dantas et al., 2018; Shaw et al., 2015; Tibana et al., 2016; Timón et al., 2019; Table 2). The timing of measures ranged from preexercise,

Table 1 Physiological Response to Benchmark CrossFit® Exercises

Authors (year)	Population	Exercise protocol	Measures	Results
Kliszczewicz et al. (2014)	Nine semi- to well-trained healthy participants with minimum of 3 months of CrossFit® participation (two women and seven men)	Cindy	VO_2|%VO_2max	33.5 ± 5.5 ml·kg^{-1}·min^{-1}|63.8 ± 12.3%
			HR_{mean}|%HR_{max}	170.8 ± 13.5 bpm|91 ± 4.2%
			Total energy expenditure	260.6 ± 59.3 kcal
			Energy expenditure	13 ± 2.9 kcal/min/3.4 ± 0.48 kcal/kg/9.5 ± 1.5 METs
Kliszczewicz et al. (2015)	10 healthy males with minimum of 3 months CrossFit® training experience	Cindy (separated by 3–7 days)	%HR_{max}	6 min: 93.3 ± 1.2%; 10 min: 94.6 ± 0.9%; 16 min: 95.9 ± 1.0%; 20 min: 97.7 ± 1.9%
			RPE (units: 0–10)	6 min: 5.4 ± 0.5; 10 min: 6.4 ± 0.5; 16 min: 7.6 ± 0.2; 20 min: 9.0 ± 0.3
			Oxidative stress	↔ post; ↑ 1-hr post: 170 ± 36.9%; ↑ 2-hr post: 351 ± 107.3%
			Protein carboxyl	↔ post: +5.4 ± 3.8%; ↑ 1-hr post: −10.6 ± 2.7%; ↑ 2-hr post: 13.0 ± 2.3%
			Blood plasma antioxidant potential (FRAP)	↑ post: +25.1 ± 2.6%; ↑ 1-hr post: +25.8 ± 4.0%; ↑2-hr post: +20.8 ± 5.1%
			Blood plasma antioxidant capacity (TEAC)	↓ post: −11.28 ± 2.4%; ↑ 1-hr post: −12.5 ± 2.6%; ↑ 2-hr post: −8.2 ± 3.2%
Fernández-Fernández et al. (2015)	10 male participants recreationally trained in CrossFit® with 12 ± 2 months experience	WOD1: Fran WOD2: Cindy (WODs performed on separate days)	[Lac]	↑ post-Fran (pre: 4.0 ± 1.3 and post: 14.0 ± 3.3 mmol/L) ↑ post-Cindy (pre: 4.0 ± 1.3 and post: 14.5 ± 3.2 mmol/L)
			VO_2|%VO_2max	Fran: 29.1 ± 1.1 ml·kg^{-1}·min^{-1}|56.7 ± 6.2% Cindy: 34.4 ± 3.5 ml·kg^{-1}·min^{-1}|66.2 ± 4.8%
			Total energy expenditure	Fran: 121.0 ± 38.5 kcal; Cindy: 318.2 ± 3.5 kcal
			HR_{mean}	Fran: 179.0 ± 8.4 bpm; Cindy: 182.2 ± 6.6 bpm
			%HR_{max}	Fran: 95.4 ± 3.0%; Cindy: 97.4 ± 2.4%
			%Time RER <1	Fran: 25.2 ± 31.1%; Cindy: 52.3 ± 21.4%
			%Time RER >1	Fran: 76.0 ± 29.7%; Cindy: 47.7 ± 21.4%
			RPE (units: 0–10)	Fran: 8.4 ± 0.9; Cindy: 8.0 ± 0.9
Escobar et al. (2017)	18 participants recreationally trained in a strength and conditioning program >1 year (11 men and seven women)	Rahoi	[Lac]	↑ postexercise (pre: 3.0 ± 1.3 and 4-min post: 10.1 ± 3.2, 8-min post: 12.3 ± 3.5, 12-min post: 12.6 ± 3.9 mmol/L)
			VO_2	37.0 ± 4.8 ml·kg^{-1}·min^{-1}
			RER	1.04 ± 0.10 units
Maté-Muñoz et al. (2017)	34 male participants recreationally trained in strength training for >6 months (including weightlifting)	Cindy	[Lac]	↑ post (pre: 1.56 ± 0.61 and post: 11.79 ± 2.33 mmol/L)
			Countermovement jump	
			Height	↓ post (−6.46%)
			Peak power	↔ post (−0.016%)
			Mean power	↓ post (−3.92%)
Maté-Muñoz et al. (2018)	32 male participants recreationally trained in strength training for >6 months (including weightlifting)	Cindy	[Lac]	↑ post (pre: 1.55 ± 0.61 and post: 12.02 ± 2.12 mmol/L)
			HR_{mean}	178 ± 9 bpm
			General RPE (units: 6–20)	17.62 ± 1.60
			Countermovement jump	
			Height	↓ post (pre: 37.99 ± 4.42 and post 35.39 ± 4.69 cm)
Tibana et al. (2018a)	13 male HIFT practitioners with minimum experience of 6 months	WOD1: Fran WOD2: FGB (WODs performed on separate days)	[Lac]	↑ post-Fran (pre: 2.3 ± 0.6 and post: 17.8 ± 4.9 mmol/L) ↑ post-FGB (pre: 2.2 ± 0.8 and post: 17.2 ± 3.5 mmol/L)
			TRIMP index	Fran: 19.8 ± 8.4 A.U.; FGB: 77.7 ± 4.9 A.U. (↑ WOD2 vs. WOD1)
			HR	↑ post-Fran (pre: 68.8 ± 8.8 and post: 182.0 ± 5.2 bpm) ↑ post-FGB (pre: 64.9 ± 14.1 and post: 184.4 ± 4.1 bpm)
			RPE (units: 0–10)	Fran: 8.7 ± 0.8; FGB: 9.6 ± 0.5 (↑ WOD2 vs. WOD1)

(continued)

Table 1 *(continued)*

Authors (year)	Population	Exercise protocol	Measures	Results
Tibana et al. (2018b)	Nine healthy men with a minimum of 6 months CrossFit® practice	WOD1: Fran WOD2: FGB (7–9 days apart)	[Lac]	Fran: pre: 2.1 ± 0.4 mmol/L; ↑ immediately post: 17.7 ± 4.2 mmol/L; ↑ 10-min post: 17.2 ± 2.2 mmol/L; ↑ 20-min post: 15.7 ± 2.3 mmol/L; ↑ 30-min post: 11.9 ± 1.7 mmol/L FGB: pre: 2.0 ± 0.7 mmol/L; ↑ immediately post: 16.2 ± 2.9 mmol/L; ↑ 10-min post: 14.4 ± 3.5 mmol/L; ↑ 20-min post: 11.1 ± 3.6 mmol/L; ↑ 30-min post: 8.7 ± 2.8 mmol/L
			[Lac] (AUC)	Fran: 15.9 ± 2.2 mmol·L^{-1}·min^{-1}; FGB: 12.6 ± 2.6 mmol·L^{-1}·min^{-1} (↑ WOD1 vs. WOD2)
			HR_{mean}|HR_{max}	Fran: 176 ± 6 bpm|186 ± 5 bpm; FGB: 174 ± 3 bpm|185 ± 3 bpm
			%HR_{max}	Fran: 91 ± 4%; FGB: 90 ± 3% (first set: 170 ± 5 bpm|88 ± 3%; second set: 175 ± 3 bpm|91 ± 3%; third set: 179 ± 4 bpm|93 ± 3%)
			RPE (units: 0–10)	Fran: 8.7 ± 0.9; FGB: 9.6 ± 0.5
Carreker and Grosicki (2020)	Eleven healthy, active men with ≥6 months of CrossFit® experience (at least twice a week)	Murph	[Lac]|Δchange HR_{mean}|HR_{max}	Post: 10.01 ± 3.04 mmol/L|↑ +7.60 ± 3.50 mmol/L 168.81 ± 6.41 bpm|185.63 ± 7.64 bpm

Note. TRIMP calculates the internal load by measuring a product of the accumulated training duration (in minutes) of five HR zones by a coefficient related to each zone (50–60% of $HR_{max} \times 1$; 60–70% of $HR_{max} \times 2$; 70–80% of $HR_{max} \times 3$; 80–90% of $HR_{max} \times 4$; and 90–100% of $HR_{max} \times 5$). Benchmark Cindy = As many rounds as possible in 20 min of five pull-ups, 10 push-ups, and 15 air squats. Benchmark Fran = 21–15–9 Reps as quickly as possible of: Thrusters (95/65 lb [~43/29 kg]), Pull-Ups. Benchmark Rahoi = As many rounds as possible in 12 minutes of: 12 Box Jumps (24 in/20 in [~61/51 cm]), 6 Thrusters (95 lbs/65 lb [~43/29 kg]), 6 Bar-Facing Burpees. Benchmark Fight Gone Bad = 3 Rounds For Total Reps in 17 minutes of: 1-min Wall Ball Shots (20/14 lb [~9/6 kg]), 1-min Sumo Deadlift High-Pulls (75/55 lb [~34/25 kg]), 1-min Box Jumps (20 in [~51 cm]), 1-min Push Press (75/55 lb [~34/25 kg]), 1-min Row (calories), 1-min Rest. Benchmark Murph = For Time: 1-mile Run, 100 Pull-Ups, 200 Push-Ups, 300 Air Squats, 1-mile Run. All performed with a Weight Vest (20/14 lb [~9/6 kg]). [Lac] = blood lactate; VO_2 = oxygen uptake; FRAP = Ferric Reducing/Antioxidant Power; VO_2max = maximal oxygen uptake; RPE = ratings of perceived exertion; bpm = beats per minute; FGB = Fight Gone Bad; MET = metabolic equivalent of task; HR = heart rate; HR_{mean} = mean HR; HR_{max} = maximal HR; A.U. = arbitrary units; WOD = workout of the day; AUC = area under the curve; TRIMP = training impulse; reps = repetitions; RER = respiratory exchange ratio; HIFT = high intensity functional training; LOOH = plasma lipid hydroperoxides; TEAC = Trolox-equivalent antioxidant capacity.

Table 2 Physiological Response to Nonbenchmark CrossFit® Exercises

Authors (year)	Population	Exercise protocol	Measures	Results
Shaw et al. (2015)	12 sedentary men	10 min of the CrossFit® triplet (CrossFit®908. 2014), three burpees, four push-ups, and five squats and upon completion of the CrossFit® exercise session	[Lac]	↑ postexercise (pre: 2.20 ± 1.35 and post: 5.95 ± 3.24 mmol/L)
			Blood glucose	↔ postexercise (pre: 105.57 ± 14.23 and post: 119.4 ± 61.25 mmol/L)
			Total cholesterol	↔ postexercise (pre: 4.10 ± 0.83 and post: 4.43 ± 0.44 mmol/L)
			HR	↑ postexercise (pre: 79.17 ± 21.96 and post: 108.00 ± 23.71 bpm)
			Systolic BP	↔ postexercise (pre: 122.92 ± 12.13 and post: 128.58 ± 27.14 mmHg)
			Diastolic BP	↔ postexercise (pre: 77.08 ± 13.10 and post: 76.00 ± 23.25 mmHg)
			Pulse pressure	↔ postexercise (pre: 44.90 ± 10.74 and post: 49.80 ± 9.36 mmHg)
			Rate pressure product	↑ postexercise (pre: 8,995.00 ± 3,434.33 and post: 11,808.60 ± 6,191.09)
			Mean arterial pressure	↔ postexercise (pre: 89.59 ± 12.03 and post: 87.89 ± 24.70 mmHg)
			FVC	↔ postexercise (pre: 4.01 ± 0.36 and post: 3.84 ± 0.35 L)
			FEV1	↓ postexercise (pre: 3.71 ± 0.37 and post: 3.53 ± 0.42 L)
			FEV1/FVC	↔ postexercise (pre: 93.56 ± 5.56 and post: 93.88 ± 5.58%)
Cronin et al. (2016)	50 well-trained CrossFit® athletes (30 men and 20 women)	WOD1 ($n = 16$), 20 of each: wall balls, sit-ups, box jumps, push-ups, hang clean, double unders, thrusters, pull-ups, overhead squats, kettlebell swings, push press, dips, sumo deadlift hi pull, burpees, back squats, glute-hamstring developers, walking lunges, dead lifts, knees to elbows, and front squats WOD2 ($n = 29$), back squat (build to tough set of five in first 12 min), AMRAP: 15 thrusters, 15 burpees, 15 ring rows, 15 pull-ups, 1,000-m row, and 15 chest to bar pull-ups WOD3 ($n = 5$), one deadlift, 15 medball cleans, 15 ring rows, 15 glute-hamstring developer sit-ups, 15 hip extensions, 4 × 5 snatch grip deadlift, 20 shoulder to overhead, 400-m run, 20 power snatches, 400-m run, 20 overhead squats, 20 dead lifts, 400-m run, 20 hang cleans, and 400-m run (Individuals performed one WOD only)	Sweat loss	
			Absolute	Men: 0.894 ± 0.284 L; women: 0.525 ± 0.174 L; ↑ in men versus women
			Rate	Men: 1.663 ± 0.478 L/hr; women: 0.886 ± 0.274 L/hr; ↑ in men versus women
			%BM	Men: 0.99 ± 0.32%; women: 0.78 ± 0.23%; ↑ in men versus women
			Fluid intake	Men: 0.592 ± 0.237 L; women: 0.565 ± 0.211 L
			Fluid replacement	Men: 75.1 ± 46.8%; women: 127.8 ± 82.1%; ↑ in women versus men
Perciavalle et al. (2016)	15 male professionals of CrossFit®	"Workout 15.5. Week 5 Open 2015" consisting of 27–21–15–9 reps for time of row (calories) and thrusters with 1-min recovery	[Lac]	↑ postexercise (pre: 4.5 ± 1.99 and post: 13.8 ± 1.18 mmol/L)
			Blood glucose	↔ preexercise: 98.3; postexercise: 99.8; 15-min postexercise: 99.3 mg/dl
			Attention Concentration Test	
			Reaction time	↑ postexercise (pre: 267.0 ± 27.91 and post: 296.0 ± 35.65 ms)
			Execution time	↑ postexercise (pre: 467 ± 27.9 ± 18.9 and post: 544 ± 32.0 ms)
			Errors	↑ postexercise (pre: 0.70 ± 0.48 and post: 2.30 ± 0.67) (number)
			Omissions	↑ postexercise (pre: 1.50 ± 0.52 and post: 2.60 ± 0.52) (number)

(continued)

Table 2 ***(continued)***

Authors (year)	Population	Exercise protocol	Measures	Results
Tibana et al. (2016)	Nine male members of the CrossFit® community with >6 months experience (mean 2.5 ± 1.2 years)	WOD1: (a) five sets of one rep of snatch (80% of 1RM) with 2- to 5-min rest intervals; (b) three sets of five touch-and-go snatches (full) at 75% 5RM with 90-s rest between sets; and (c) three sets of 60 s of weighted plank hold with 90-s rest; following 5-min rest, endurance conditioning was performed with 10 min of AMRAP 30 double unders and 15 power snatches (34 kg) WOD2: (a) five sets of one rep of clean and jerk (80% 1RM) with 2- to 5-min rest intervals; (b) three sets of five touch-and-go cleans (full) at 70% 5RM with 2- to 5-min rest; and (c) three sets of 10 strict hand standing push-ups; following 5 min of rest, endurance conditioning with 12-min AMRAP of rowing (250 m) and 25 target burpees (WODs were performed on consecutive days)	[Lac]	↑ post-WOD1 (pre: 1.20 ± 0.41 and post: 11.84 ± 1.34 mmol/L) ↑ post-WOD2 (pre: 0.94 ± 0.34 and post: 9.05 ± 2.56 mmol/L)
			Blood glucose	↑ post-WOD1 (pre: 81.59 ± 10.27 and post: 114.99 ± 12.52 mmol/L) ↑ post-WOD2 (pre: 69.47 ± 6.97 and post: 89.95 ± 19.26 mmol/L)
			ΔChange IL-6	↑ post-WOD1: +4.1 ± 1.9 pg/ml (+197 ± 109%) ↑ post-WOD2: +3.3 ± 2.6 pg/ml (+99 ± 58%)
			ΔChange IL-10	↔ post-WOD1: 14.4 ± 17.8 pg/ml (44 ± 52%) ↑ post-WOD2: 21.4 ± 69.9 pg/ml (21 ± 70%)
			ΔChange IL-10/IL-6 ratio	↓ post-WOD1: –43 ± 24%; ↓ post-WOD2: –49 ± 27%
			ΔChange osteoprotegerin	↔ post-WOD1: –0.02 ± 0.09 ng/mL; ↔ post-WOD2: +0.04 ± 0.09 ng/mL
			Muscular power output by linear position transducer	
			MPO	↓ MPO immediately post-WOD1 and WOD2 pre-WOD1: 691 W; post-WOD1: 636 W; 24-hr post-WOD1: 698 W post-WOD2: 628 W; 24-hr post-WOD2: 686 W
			PPO	↑ PPO 24 hr after WOD2 versus preintervention pre-WOD1: 1,410 W; post-WOD1: 1,480 W; 24-hr post-WOD1: 1,520 W post-WOD2: 1,500 W; 24-hr post-WOD2: 1,530 W
Maté-Muñoz et al. (2017)	34 male participants recreationally trained in strength training for >6 months (including weightlifting)	WOD1[a]: As many double unders as possible in eight sets of 20 s with 10 s of rest between sets WOD2[a]: Maximum number of power cleans in 5-min lifting 40% of individual 1RM	[Lac]	↑ post-WOD1 (pre: 1.30 ± 0.37 and post: 10.15 ± 3.04 mmol/L) ↑ post-WOD2 (pre: 1.22 ± 0.31 and post: 11.24 ± 2.62 mmol/L)
			Countermovement jump	
			Height	↓ post-WOD1 (–3.56%); ↓ post-WOD2 (–7.35%)
			Peak power	↔ post-WOD1 (+0.56%); ↓ post-WOD2 (–2.76%)
			Mean power	↔ post-WOD1 (–1.82%); ↓ post-WOD2 (–7.31%)
Maté-Muñoz et al. (2018)	32 male participants recreationally trained in strength training for >6 months (including weightlifting)	WOD1[a]: As many double unders as possible in eight sets of 20 s with 10 s of rest between sets WOD2[a]: The maximum number of power cleans possible in 5-min lifting 40% of individual 1RM	[Lac]	↑ post-WOD1 (pre: 4.00 ± 1.30 and post: 14.50 ± 3.20 mmol/L) ↑ post-WOD2 (pre: 1.23 ± 0.32 and post: 11.49 ± 2.59 mmol/L)
			HR_{mean}	WOD1: 178 ± 9 bpm; WOD2: 171 ± 11 bpm
			General RPE (units: 6–20)	WOD1: 16.00 ± 2.32; WOD2: 15.65 ± 2.02
			Countermovement jump	
			Height	↓ post-WOD1 (pre: 37.05 ± 4.37 and post: 36.63 ± 4.66 cm) ↓ post-WOD2 (pre: 36.57 ± 4.13 and post: 33.82 ± 4.97 cm)
Coco et al. (2019)	15 male professional bodybuilders	"Workout 15.5. Week 5 Open 2015" consisting of 27–21–15–9 reps for time of rowing (calories) and thrusters with 1-min recovery	[Lac]	↑ postexercise (pre: 3.16 ± 0.64 and post: 6.34 ± 1.59 mmol/L)
			Blood glucose	↔ postexercise (pre: 94.76 ± 7.93 and post: 97.07 ± 7.87 mmol/L)
			Attention Concentration Test	
			Reaction time	↑ postexercise (pre: 183.4 ± 26.2 and post: 246.3 ± 29.6 ms)
			Execution time	↑ postexercise (pre: 425.3 ± 18.9 and post: 484.0 ± 13.5 ms)
			Errors	↑ postexercise (pre: 0.56 ± 0.51 and post: 2.50 ± 0.51)
			Omissions	↑ postexercise (pre: 1.37 ± 0.50 and post: 2.81 ± 0.40)

(continued)

Table 2 *(continued)*

Authors (year)	Population	Exercise protocol	Measures	Results
Moreira et al. (2019)	13 participants recreationally trained in high-intensity training program (nine women and four men)	"Open 16.5" consisting on sets of 21, 18, 15, 12 9, 6, and 3 reps of thrusters and burpees. The standardized weight for thruster was 40 kg for men and 25 kg for women	[Lac]	↑ 3-min postexercise (pre: 2.7 ± 0.8 and post: 9.6 ± 2.2 mmol/L) (overall) ↑ postexercise in men (+8.8 ± 1.7 mmol/L) versus women (+5.9 ± 2.3 mmol/L)
			RPE (units: 0–10)	9.5 ± 0.9 (women: 9.8 ± 0.4; men: 9.0 ± 1.2)
			Total sweat loss	394 ± 155 ml (women: 386 ± 159 ml; men: 413 ± 155 ml)
			Sweat rate	23.8 ± 9.6 ml/min (women: 22.7 ± 10.5 ml/min; men: 26.3 ± 7.8 ml/min)
Timón et al. (2019)	12 male participants trained in CrossFit® at least 1 year of experience in CrossFit® training with 2 days of training a week	WOD1[a]: AMRAP of burpees and toes to bar increasing reps (1–1. 2–2. 3–3 . . .) in 5 min WOD2[a]: Rounds for time consisting of three rounds of 20 reps of wall ball (9 kg) and 20 reps of power clean (a load of 40% 1RM) in the shortest possible time	[Lac]	↑ post-WOD1 (13.30 ± 1.87 mmol/L); ↑ post-WOD2 (18.38 ± 2.02 mmol/L)
			Blood glucose	↑ post-WOD1 (+37.4%), ↔24-hr post-WOD1 (–2.6%), ↔ 48-hr post-WOD1 (–2.8%) ↑ post-WOD2 (+71.5%), ↔24-hr post-WOD2 (–12.0%), ↔ 48-hr post-WOD2 (–3.0%)
			BUN	↔ post-WOD1 (+1.1%), ↔24-hr post-WOD1 (–2.2%), ↔ 48-hr post-WOD1 (–4.5%) ↔ post-WOD2 (–1.4%), ↔ 24-hr post-WOD2 (–12.5%), ↔ 48-hr post-WOD2 (–0.9%)
			TBIL	↔ post-WOD1 (+17.2%), ↔ 24-hr post-WOD1 (–6.8%), ↔ 48-hr post-WOD1 (–3.44%) ↑ post-WOD2 (+24.0%), ↑ 24-hr post-WOD2 (+40.0%), ↔ 48-hr post-WOD2 (+20.0%)
			GOT	↑ post-WOD1 (+58.6%), ↔ 24-hr post-WOD1 (+11.3%), ↔ 48-hr post-WOD1 (–17.8%) ↑ post-WOD2 (+58.5%), ↑ 24-hr post-WOD2 (+23.8%), ↔ 48-hr post-WOD2 (–2.0%)
			GPT	↑ post-WOD1 (+109.0%), ↔ 24-hr post-WOD1 (+9.4%), ↔ 48-hr post-WOD1 (–7.5%) ↑ post-WOD2 (+122.0%), ↑ 24-hr post-WOD2 (+18.0%), ↔ 48-hr post-WOD2 (+1.4%)
			LDH	↔ post-WOD1 (+11.5%), ↔ 24-hr post-WOD1 (+17.3%), ↔ 48-hr post-WOD1 (+17.0%) ↔ post-WOD2 (–4.4%), ↔ 24-hr post-WOD2 (+10.9%), ↔ 48-hr post-WOD2 (–3.0%)
			CPK	↑ post-WOD1 (+21.7%), ↑ 24-hr post-WOD1 (+52.6%), ↔ 48-hr post-WOD1 (–14.3%) ↑ post-WOD2 (+22.7%), ↑ 24-hr post-WOD2 (+65.6%), ↔ 48-hr post-WOD2 (+1.0%)
			HR_{max}	WOD1: 177.8 ± 11.2 bpm; WOD2: 184.2 ± 8.6 bpm
			HR_{mean}	WOD1: 127.6 ± 11.1 bpm; WOD2: 159.8 ± 12.1 bpm
			RPE (units: 0–10)	WOD1: 7.2 ± 1.3; WOD2: 8.2 ± 0.4
			Plank test	↓ post-WOD1 (–34.7%), ↓ 24-hr post-WOD1 (–27.7%), ↔ 48-hr post-WOD1 (–7.2%) ↓ post-WOD2 (–45.0%), ↓ 24-hr post-WOD2 (–23.7%), ↔ 48-hr post-WOD2 (–9.0%)
			Countermovement jump	↔ post-WOD1 (+ 6.8%), ↔ 24-hr post-WOD1 (–4.9%); ↔ 48-hr post-WOD1 (–2.1%) ↔ post-WOD2 (+4.5%), ↔ 24-hr post-WOD2 (–2.6%), ↔ 48-hr post-WOD2 (–1.1%)

Note. RPE = ratings of perceived exertion; HR = heart rate; HR_{mean} = mean HR; HR_{max} = maximal HR; FEV1 = forced expiratory volume in 1 s; PPO = peak power output; FVC = forced vital capacity; MPO = mean power output; CPK = creatine phosphokinase; LDH = lactate dehydrogenase; AMRAP = as many rounds as possible; BP = blood pressure; BUN = blood urea nitrogen; TIBL = total bilirubin; GOT = glutamic oxaloacetic transaminase; GPT = glutamic pyruvic transaminase; rep = repetition; RM = rep maximum; [Lac] = blood lactate; WOD = workout of the day; Δchange = preexercise to postexercise change; IL = interleukin; BM = body mass.

[a] WODs were performed on separate days.

Table 3 Dietary and Supplement Intervention Studies on CrossFit® Performance

Authors (year)	Population	Intervention	Performance protocol and measures	Results
Outlaw et al. (2014)	13 males and 16 females trained in CrossFit® with >6 months experience	6 weeks of preworkout and postworkout supplementation alongside routine CrossFit® training SUP consisted of 19 g of a preworkout drink (extracts of pomegranate, tart cherry, beetroot, and green and black tea) taken 30 min before training and a postworkout protein (females: 20 g; males: 40 g) and CHO (females: 40 g; males: 80 g) supplement consumed immediately after each workout. The CON group consumed only water 1 hr before or after workouts	WOD1: 500-m row, 40 wall balls, 30 push-ups, 20 box jumps, 10 thrusters as quickly as possible (TTC) WOD2: 800-m run, AMRAP of five burpees, ten kettlebell swings, 15 air squats within 15 min (reps) Graded exercise test (VO$_2$max) 30-s cycling Wingate (PPO and MPO) Body composition	↑ TTC, SUP: + 5.85%, CON: +2.39%. ↔ difference between groups. ↑ Reps, SUP: + 10.01%, CON: +2.41%. ↑ *likely beneficial* improvement for SUP versus CON ↑ VO$_2$max *likely beneficial* for SUP ↑ PPO *likely beneficial* for SUP, ↔ MPO ↔ Body composition pre- to postintervention
Escobar et al. (2016)	18 individuals (11 females and seven males) with a strength and conditioning experience of ≥3 days per week for a minimum of 1 year	9-day training protocol with CHO-rich diet or CON: Group CHO and CON: Days 1–5: <6 g·kg^{-1}·day^{-1}; Group CHO: Days 6–8: 6–8 g·kg^{-1}·day^{-1}, whereas the CON group maintained their current intake of <6 g·kg^{-1}·day^{-1} CrossFit® performance was assessed on Days 1, 5, and 9	Benchmark Rahoi (reps) VO$_2$ and RER [Lac] (preexercise; 4-, 8- and 12-min postexercise)	↑ reps on Day 9 versus Days 1 and 5 for both CHO (+10.9%) and CON (+4.2%), ↔ between groups ↑ VO$_2$ from Day 1 to Day 9 for both CHO and CON ↔ RER ↔ [Lac] between days at all time points except 8-min postexercise, which was ↑ from Day 1 to Day 9 for both CHO and CON
Kramer et al. (2016)	12 male CrossFit® athletes with ≥4 months experience training ≥3 time/week	Six days of SUP with (NO) (2 × 4 mmol capsules of potassium NO, one consumed in the morning, one in the evening) or a noncaloric PLA	30-s cycling Wingate (PPO) 2,000-m rowing Isokinetic and isometric extension and flexion strength testing Grace Benchmark	↑ PPO NO (889.17 ± 179.69 W to 948.08 ± 186.80 W), ↔ PPO PL (898.08 ± 183.24 W to 905.00 ± 157.23 W) ↔ pre- to postintervention for both NO and PLA ↔ pre- to postintervention for both NO and PLA ↔ pre- to postintervention for both NO and PLA
Gregory et al. (2017)	27 nonelite CrossFit members (five males and 22 females)	6 weeks of a LCKD while participating in four CrossFit workouts per week Participants on the LCKD ($n = 12$) received dietary guidelines to be followed for 6 weeks (<50 g/day CHO), whereas participants in the CON group were instructed to continue their normal diet during the study	CrossFit Performance test (500-m row; 40 body weight squats 30 abdominal mat sit-ups; 20 hand release push-ups; 10 pull-ups) Vertical and standing long jump Body weight %BF FM LBM	↔ from pre- to postintervention for LCKD and CON ↔ from pre- to postintervention for LCKD and CON ↓ −3.45 ± 2.18 kg for LCKN at 6 weeks, ↔ CON ↓ −2.60 ± 2.14% for LCKN at 6 weeks, ↔ CON ↓ −2.83 ± 1.77 kg for LCNK at 6 weeks, ↔ CON ↔ from pre- to postintervention for LCKD and CON
Rountree et al. (2017)	Eight healthy, college-aged, CrossFit® trained males with >3 months CrossFit® experience and >6 months resistance training	CHO (6% sucrose/dextrose solution) beverage before and throughout exercise: 16 g of CHO in approximately 250 ml of fluid over 30 min. PLA was a noncaloric sucralose and aspartame beverage	FGB (Total AMRAP; reps/round)	↔ total work between CHO (321 ± 51 reps) and PLA (314 ± 52 reps) ↔ reps in every round between CHO and PLA

(continued)

Table 3 *(continued)*

Authors (year)	Population	Intervention	Performance protocol and measures	Results
Ahmad et al. (2018)	17 physically active men who had cardio and strength training at least three times a week	500 ml ZM juice drinks (285 kcal, 49 g CHO, 12 g protein, 4.5 g fat, 321.5 mg sodium) or 700 ml CE (282 kcal, 68 g CHO, 469.6 mg sodium) consumed within 30 min after a Cindy Benchmark. Another execution of the Cindy Benchmark 2 hr after the first	Benchmark Cindy (Total number of reps during the second Cindy) HR, [Lac], and RPE	↑ total reps with ZM juice ZM: SET1 = 6.6 ± 1.9 reps, SET2 = 6.8 ± 2.3 reps; CE: SET1 = 6.5 ± 1.9 reps, SET2 = 6.2 ± 1.9 reps ↔ HR, [Lac], and RPE between drinks
Durkalec-Michalski et al. (2018)	21 participants recreationally and regularly training in CrossFit® (nine women and 12 men)	Progressive-dose SB or PLA SUP for 10 days (Days 1–2: 37.5 mg/kg; Days 3–4: 75 mg/kg; Days 5–7: 112.5 mg/kg; Days 8–10: 150 mg/kg)	FGB (Number of total reps and correctly performed reps) Incremental cycling test (TTE; maximum workload; workload at VT; HR)	↑ total reps with SB (pre: 266.4 ± 40.2 reps vs. post: 282.6 ± 37.9 reps) ↑ correctly performed reps in Round 1 (+5.8%), Round 2 (+6.4%), and Round 3 (+6.2%) with SB ↑ workload at VT (+4.0%) and ↑ time to reach VT (pre: 7:58 ± 2:12 min, post: 8:25 ± 2:28 min) with SB ↔ TTE, maximum workload, or maximum HR
Kephart et al. (2018)	12 participants (nine males and three females) with >3 months CrossFit® experience	12 weeks of a KD while participants continued their habitual CrossFit® training KD participants ($n = 7$) were given dietary guidelines to follow over 12 weeks, whereas CON group participants were instructed to continue their normal diet throughout the study All participants continued their CrossFit® training routine for 12 weeks Variables were assessed at Weeks 0, 2.5, and 12	1RM for back squat and power clean Maximal rep push-up test to volitional fatigue 400-m run (TTC) BHB levels BM (kg) FM (%) LBM (%) Vastus lateralis thickness (cm) FG, HDL and LDL, and TGL	↔ from pre- to postintervention for KD and CON ↑ push-ups from pre- to postintervention for both KD and CON with no difference between groups ↔ from pre- to postintervention for KD and CON ↑ 2.8- to 9.5-fold higher in KD versus CON ↓ for KD but not CON ↓ 12.4% at Week 12 in KD ($p = .053$) ↔ from pre- to postintervention for KD and CON ↔ from pre- to postintervention for KD and CON ↔ FG, HDL, and TGL from pre- to postintervention for KD and CON. LDL: ↑ approximately 35% in KD, ↓ in CON
Sadowska-Krepa et al (2019)	16 young males involved in CrossFit® training	6-week GTE SUP alongside CrossFit® training Two capsules were administered once daily for 6 weeks, each capsule containing 250 mg of GTE, 245 mg polyphenols, 200 mg catechins, and <4 mg CAF or placebo (PLA). CrossFit® workout was based on the CrossFit training guide composed of three distinct modalities: monostructural metabolic conditioning, gymnastics, and weightlifting. Each training unit was represented by involving one, two, or three modalities	Incremental cycle to exhaustion (40 W + 40 W/3 min) to determine VO$_2$max Glutathione (GSH) SOD CAT, GPx, and GR UA Total phenolics Total antioxidant capacity (FRAP) Lipid peroxidation products (TBARS) BDNF	↔ VO$_2$max from pre- to postintervention GTE, pre: 45.6 ± 5.6, post: 48.8 ± 4.6 ml·kg^{-1}·min^{-1}; PLA, pre: 45.5 ± 5.4, post: 47.3 ± 5.4 ml·kg^{-1}·min^{-1} ↔ GSH from pre- to postintervention ↑ SOD at rest and postexercise for both GTE and PLA postintervention ↔ CAT, GPx, and GR from pre- to postintervention in both groups ↑ UA during recovery from exercise with GTE (+19.8%) and PLA (+32%) ↑ GTE and ↓ PLA from pre- to postintervention ↑ pre- to postintervention for both groups, GTE: +44%, PLA: +24% ↓ GTE and ↑ PLA from pre- to postintervention ↑ BDNF from pre- to postintervention for both GTE and PLA

(continued)

Table 3 ***(continued)***

Authors (year)	Population	Intervention	Performance protocol and measures	Results
Moro et al. (2020)	29 participants (14 females and 15 males) with at least 6 months CrossFit® experience	6-week BET group received 1.25 g of BET (in 8 g of microcrystalline cellulose) twice a day (total: 2.5 g/day) and PLA group received the same amount of inert compound (microcrystalline cellulose and flavors) Performance was assessed using three tests: 3RM back-squat for muscle strength; 2-km rowing test for aerobic capacity; and Bergeron Beep test for anaerobic capacity	3RM squat test 2-km row test Bergeron Beep test FM and FFM ACM PA TBW WB	↑ BET (+3.23%), ↔ PLA (+2.05%) ↔ BET (-0.43%) and PLA (+0.43%) ↔ BET (+8.38%) and PLA (+6.35) ↔ FM, FFM, ACM, PA, TBW, and WB from pre- to postintervention
Fogaça et al. (2020)	Nine male CrossFit® athletes with at least 1 year experience in CrossFit® and categorized as intermediary level	Acute CAF or PLA SUP: 6 mg/kg 60 min before a CrossFit® workout CrossFit® workout: 5 × 1 rep of snatch from the block with load at 80% 1RM; 3 × 5 reps of touch-and-go snatches at 75% of 1RM; 3 × 60 s of isometric weighted plank (11.4 kg); 10 min of AMRAP of 30 double unders and 15 power snatches (34 kg)	AMRAP of 30 double unders and 15 power snatches (34 kg). Countermovement jump Dynamic strength Blood glucose CK, DOMS, and RPE	↔ AMRAP between CAF and PLA ↔ between CAF and PLA ↔ between CAF and PLA ↑ glucose concentration after workout in CAF (+3.2 mmol/L) compared with PLA (+1.5 mmol/L) ↔ CK, DOMS, and RPE between CAF and PLA
Schwarz et al. (2020)	11 healthy participants (six women and five men) with >6 months CrossFit®-style training and previously performed the 15.5 CrossFit® Open Workout successfully at least once	200 mg of 98% pure EPI or cellulose (PLA) ingested daily for 2 days and 60–90 min before completing the CrossFit® workout	15.5 CrossFit® Open Workout (rowing, followed by barbell thrusters completed for four rounds with the goal to finish as fast as possible; split times were recorded after finishing each exercise of each round as well as TTC)	↔ TTC between EPI and PLA ↔ split times between EPI and PLA
Stein et al. (2020)	20 CrossFit®-trained men with ≥6 months of CrossFit® experience	Acute CAF or PLA SUP: 5 mg/kg of CAF or 300 µg biotin as PLA 60 min before exercise	Benchmark Cindy (reps) Postexercise RPE (units: 0–10)	↔ reps between CAF (468.6 ± 114.7 reps) and PLA (466.7 ± 94.3 reps) ↔ RPE between CAF (8.3 ± 0.3) and PLA (8.2 ± 0.3)

Note. RPE = ratings of perceived exertion; PPO = peak power output; MPO = mean power output; AMRAP = as many rounds as possible; rep = repetition; 1RM = one-rep maximum; WOD = workout of the day; SUP = supplementation; TTC = time to completion; VO_2max = maximal oxygen uptake; VO_2 = oxygen uptake; CHO = carbohydrate; [Lac] = blood lactate; NO = nitrate; PLA = placebo; LCKD = low-CHO ketogenic diet; BM = body mass; BF = body fat; FM = fat mass; LBM = lean BM; FGB = Fight Gone Bad; ZM = Zea Mays; HR = heart rate; SB = sodium bicarbonate; VT = ventilator threshold; KD = ketogenic diet; BHB = blood beta hydroxybutyrate; FG = fasting glucose; HDL = high-density cholesterol; LDL = low-density cholesterol; TGL = triglycerides; GTE = green tea extract; SOD = superoxide dismutase; CAT = catalase; GPx = glutathione peroxidase; GR = reduced glutathione; UA = uric acid; BDNF = brain-derived neurotrophic factor; BET = betaine; FFM = fat-free mass; ACM = active cellular mass; PA = phase angle; TBW = total body water; WB = water balance; FRAP = Ferric Reducing/Antioxidant Power; EPI = (-)-epicatechin; CAF = caffeine; CE = Carbohydrate-electrolyte; CON = control; RER = respiratory exchange ratio; CK = creatine kinase; DOMS = Delayed onset of muscle soreness. TBARS = Thiobarbituric acid reaction; TTE = Time to exhaustion; GSH = Glutathione;

immediately postexercise, and up to 48-hr postexercise. The most commonly measured blood variables included [Lac] and glucose, whereas other physiological measures taken before, during, and after exercise included oxygen uptake, HR, energy expenditure, forced vital capacity, blood pressure, cholesterol, and interleukin-6 and 10, among others. Two studies evaluated hydration during CrossFit® exercise, reporting on sweat rates and losses induced by a CrossFit® workout (Cronin et al., 2016; Moreira et al., 2019). Ratings of perceived exertion (RPE) were frequently used to assess the individual's perception of effort. Muscular fatigue induced by CrossFit® exercises was measured in some studies using countermovement jump tests (Maté-Muñoz et al., 2017, 2018; Timón et al., 2019), linear position transducer (Tibana et al., 2016), and the plank test (Timón et al., 2019), whereas mental fatigue was assessed in two studies using the Attention Concentration Test (Coco et al., 2019; Perciavalle et al., 2016).

All protocols measuring [Lac] showed increased values from preexercise to postexercise (range: 5.95–18.38 mmol/L; Tables 1 and 2). Glycemic variation was investigated by five studies, two of which showed significant increases in blood glucose immediately after CrossFit® exercise (Tibana et al., 2016; Timón et al., 2019), whereas three studies (Coco et al., 2019; Perciavalle et al., 2016; Shaw et al., 2015) did not show any changes. The HR throughout CrossFit® exercises was high with mean HRs during Benchmark WODs such as Fran, Cindy, and FGB in excess of 90% of maximum HR. Oxygen uptake during Fran and Cindy was between 55% and 65% of maximal oxygen uptake with substantial time spent with a respiratory exchange ratio above one. Total energy expenditure during Cindy appeared to be higher than during Fran (Fernández-Fernández et al., 2015; Table 1). The intense nature of these activities was reflected in high RPE scores across different WODs. Markers of muscle damage and inflammation were increased immediately postexercise and as much as 24-hr postexercise. Muscle fatigue was induced by CrossFit® exercise immediately postexercise following most exercise protocols, lasting up to 24 hr post-WOD (Timón et al., 2019), although it was generally no longer evident 48-hr postworkout. Reaction and execution time during the Attention Concentration Test was impaired immediately following CrossFit® exercise with a higher number of errors and omissions, although cognitive performance returned to baseline following 15-min recovery. Quality ratings for the studies in Part A were low ($n = 3$; 17.6%), moderate ($n = 11$; 64.7%), and high ($n = 3$; 17.6%; see Supplementary Table S1 [available online]).

Part B

Thirteen studies investigated the effects of dietary and supplementation interventions on various aspects of CrossFit® performance (Table 3). Dietary interventions included a 9-day training protocol alongside a carbohydrate (CHO)-rich or control diet (for the last 3 days) on Benchmark Rahoi performance (Escobar et al., 2016) and a 6- (Gregory et al., 2017) and 12-week (Kephart et al., 2018) ketogenic diet (KD) or control diet throughout CrossFit® training with performance assessed via a battery of anaerobic performance tests (Table 3). Supplementation studies included caffeine (Fogaça et al., 2020; Stein et al., 2020), sodium bicarbonate (SB; Durkalec-Michalski et al., 2018), nitrate (Kramer et al., 2016), and betaine (Moro et al., 2020) interventions as well as CHO (Rountree et al., 2017), epicatechin (Schwarz et al., 2020), and *Zea Mays* juice (Ahmad et al., 2019). Six weeks of green tea extract (GTE) supplementation alongside structured CrossFit® training (Sadowska-Krepa et al., 2019) and 6 weeks of preworkout and postworkout protein–CHO supplementation alongside routine CrossFit® training (Outlaw et al., 2014) were also investigated. Their performance effects were measured using a wide range of CrossFit® Benchmark WODs, such as FGB, Cindy, Grace, Rahoi, and various other CrossFit® workouts. Some studies also measured the effects of these supplementation and dietary interventions on incremental cycling capacity (i.e., maximal oxygen uptake) and 30-s cycling Wingate performance (Kramer et al., 2016; Outlaw et al., 2014; Sadowska-Krepa et al., 2019; Table 3).

Escobar et al. (2017) had two groups consume a low-CHO diet (<6 $g \cdot kg^{-1} \cdot day^{-1}$) for 5 days, after which one group increased their daily CHO intake to 6–8 $g \cdot kg^{-1} \cdot day^{-1}$ for 3 days. CrossFit® performance was assessed on Days 1, 5, and 9. An increased number of repetitions was shown on Day 9 compared with Day 1 for both groups with no statistical difference between diets (Table 3). A 12- and 6-week KD alongside routine training did not lead to any further performance gains compared with a control group (Gregory et al., 2017; Kephart et al., 2018), although body mass (BM) and fat mass losses were greater with the KD (Table 3). The GTE combined with CrossFit® training did not lead to any gains in incremental exercise capacity and was not different to placebo (Sadowska-Krepa et al., 2019), although some beneficial effects were shown on antioxidant capacity and brain-derived neurotrophic factor with training (Table 3). The SB improved the total number of repetitions performed during FGB (Durkalec-Michalski et al., 2018), whereas potassium nitrate supplementation improved peak power output during a 30-s Wingate but did not affect 2,000-m rowing, isokinetic and isometric extension, or Benchmark Grace performance (Kramer et al., 2016; Table 3). Two studies that supplemented 5–6 mg/kg BM caffeine did not show performance improvements in CrossFit® exercise (Fogaça et al., 2020; Stein et al., 2020). A *Zea Mays* juice drink improved performance during CrossFit® Benchmark Cindy compared with a CHO–electrolyte solution (Ahmad et al., 2019; Table 3). Quality rating for the studies in Part B were very low ($n = 1$; 7.7%), low ($n = 4$; 30.8%), moderate ($n = 3$; 23.1%), and high ($n = 4$; 30.8%; see Supplementary Table S2 [available online]).

Discussion

This systematic review showed that CrossFit® WODs (Benchmarks, Open competitions, and training workouts) are composed of intense, physically demanding exercises that rely heavily on both aerobic and anaerobic energy metabolism. Scarce research exists to support dietary or nutritional strategies that might benefit aspects of CrossFit® performance, and research was generally of moderate to low quality.

The physiological and metabolic responses to CrossFit® WODs were similar across different exercises, showing high values for HR, oxygen uptake, total energy expenditure, and [Lac] during and immediately following execution. This is indicative of high-intensity activity that requires substantial energy contribution with both aerobic and anaerobic components. The high-intensity nature of CrossFit® is also highlighted in high RPE scores across studies. The perceived demands of CrossFit® are higher than those of general exercise guidelines, such as those from the American College of Sports Medicine (Drum et al., 2017). Although different exercises can lead to slightly different physiological responses and RPE (Mate-Munoz et al., 2018; Tibana et al., 2018b), all CrossFit® WODs are very high intensity in nature. CrossFit® Benchmarks, specifically, show very similar physiological responses (e.g., HR, oxygen uptake, [Lac]) despite different durations and specific exercise tasks (Table 1). The glycemic response to CrossFit® was highly variable with some studies showing increases in blood glucose immediately after CrossFit® exercise and others showing no changes. A lack of standardization (i.e., dietary control) prior to the experimental protocols in some studies might have contributed to these inconsistent results. Exercise can improve insulin sensitivity and glycemic control for up to 72-hr postactivity (Sigal et al., 2006), although the only study to measure blood glucose 24- and 48-hr post-CrossFit® did not show any changes at these time points (Timón et al., 2019). Chronic exercise training may improve pancreatic beta-cell function (Slentz et al., 2009), although the optimal exercise training intensity (low, moderate, and high) to maximize these adaptations is unknown (Goodwin, 2010). Further studies are required to elucidate the effect of a CrossFit® workout on blood glucose and how this translates into chronic effects on glycemic control with CrossFit® training.

Muscle fatigue due to CrossFit® exercise is evident with countermovement jump performance impaired at various moments throughout and following various WODs (Maté-Muñoz et al., 2017, 2018), although not in all studies (Timón et al., 2019), suggesting that not all CrossFit® WODs are equally fatiguing. In one study in which three CrossFit® training modalities were assessed, reflecting gymnastics, cardiovascular exercise, and weightlifting, muscle fatigue was shown throughout the cardiovascular exercise (eight sets of 20-s double under skip rope jumps with 10-s rests between sets) but not when assessed 3-min postexercise (Maté-Muñoz et al., 2018). Benchmark Cindy (gymnastics) and as many repetitions as possible of power cleans (weightlifting) in 5 min also impaired countermovement jump performance throughout the exercise task, and the impairment remained following 3-min recovery. Athletes are likely to perform combinations of these exercises, exacerbating fatigue. Increased muscle fatigue appears to coincide with pro-inflammatory markers and measures of muscle damage (Tibana et al., 2016; Timón et al., 2019). Importantly, this muscle fatigue and markers of muscle damage and inflammation can persist for up to 24-hr post-WOD (Timón et al., 2019), although by 48-hr post-WOD, these returned to baseline levels. This suggests that a larger volume or intensity of CrossFit® WODs may lead to greater inflammation and muscle damage and, consequently, a slower recovery from muscle fatigue. This is a point worth considering when planning and performing repeated CrossFit® bouts or training sessions on subsequent days. Nutritional considerations such as CHO and protein ingestion should be prioritized to elicit optimal adaptations and avoid potential injury. Certainly, these results highlight the need for studies to further assess the intensity and physiological demands of different CrossFit® protocols, determine safe intervals between WODs, and guide optimal nutrition strategies.

Two studies (Coco et al., 2019; Perciavalle et al., 2016) evaluated attentional performance using the Attention Concentration Test after the execution of the 2015 Workout 15.5 WOD, both showing impaired reaction and execution time, coupled to an increase in the number of errors and omissions, immediately post-WOD, suggesting diminished cognitive function following a CrossFit® workout. Concentration test performance returned to baseline following 15-min recovery. It is worth mentioning that a correlation was shown between the drop in attention and the increase in [Lac] values, suggesting that the increase in post-WOD lactate could interfere with cognitive domains related to attention, although correlation does not imply causation. Lactate has long been considered a villain and is associated with ischemia in the brain, as brain metabolism is almost entirely oxidative (Watts et al., 2018). However, more recent evidence suggests that lactate acts as a signaling molecule in the brain (Magistretti & Allaman, 2018) and is even used as a fuel source for cognitive functioning (Gallagher et al., 2009). Interestingly, lactate may even be an important energy source for the brain during high-intensity exercise (Adeva-Andany et al., 2014). The potential long-term benefits of high-intensity exercise on cognitive function are hotly debated but could occur via a number of mechanisms (Calverley et al., 2020). Although long-term benefits of CrossFit® may be shown for brain function, caution is advised, as these data suggest that attention and concentration are somewhat impaired immediately following high-intensity WODs. This is a potential issue, which should be considered in relation to CrossFit® injury rates (Hak et al., 2013; Hopkins et al., 2019; Weisenthal et al., 2014), particularly for those WODs requiring high levels of technique, and is an interesting avenue for further research.

CrossFit® is clearly a highly metabolically demanding sport with a substantial proportion of energy requirements coming from anaerobic sources. Thus, nutritional strategies aimed at optimizing CHO provision might be beneficial to performance. However, a 6% sucrose/dextrose solution (total 16 g of CHO) throughout an FGB Benchmark did not improve performance compared with placebo (Rountree et al., 2017). A CHO–protein drink (*Zea Mays* juice) ingested immediately following the Benchmark Cindy led to an improved performance during the subsequent Cindy (performed 2 hr later) compared with a CHO–electrolyte drink (Ahmad et al., 2019). As the CHO content of the CHO–electrolyte drink was higher than the *Zea Mays* juice (68 vs. 49 g), these improvements cannot be attributed to the CHO. The extent to which acute CHO supplementation during CrossFit® exercise benefits performance is currently unclear, as evidence is limited. This might also be due to issues in study design, as the quality of these intervention studies was considered low to moderate, although it is not unfeasible to suggest that, despite their intense nature, isolated CrossFit® WODs are of too short a duration to be influenced by CHO supplementation (Jeukendrup, 2014). More studies with longer or repeated-bout CrossFit® WODs are required to elucidate the importance of acute CHO supplementation for performance.

Six weeks of post-CrossFit® training supplementation of a CHO–protein drink led to benefits in some aspects of CrossFit® performance (Outlaw et al., 2014), although these effects cannot be isolated, as participants also ingested a preworkout pomegranate fruit extract containing polyphenols and nitrates. A 3-day-rich diet (6–8 $g \cdot kg^{-1} \cdot day^{-1}$) alongside training did not lead to greater improvements in Rahoi performance compared with a control diet (<6 $g \cdot kg^{-1} \cdot day^{-1}$; Escobar et al., 2017). Specifically, performance was improved for both groups but with no difference between diets, suggesting that both a low- and high-CHO diet are equally effective alongside CrossFit® training to improve performance. The high CHO intake in this study was below the recommended range of 8–12 $g \cdot kg^{-1} \cdot day^{-1}$ for maximal supercompensation of muscle glycogen stores (Thomas et al., 2016b), meaning that greater CHO intake might have led to different results. Nonetheless, performance changes were twice as large in the high-CHO group (+10.9% vs. 4.2%), and a lack of difference between groups might have been due to the small sample size (Escobar et al., 2017). In addition, the low-CHO diet group maintained approximately 3.13–3.73 $g \cdot kg^{-1} \cdot day^{-1}$ CHO, which is above the typical intake for a nonketogenic low-CHO diet (Burke, 2020). This daily CHO ingestion may have been sufficient to maintain the daily energy demands of the exercise, further explaining the lack of difference between groups.

Two studies investigated the effect of low-CHO diets on CrossFit® performance. A 12-week instructed KD alongside usual CrossFit® training did not impact performance measures, although whole-body adiposity was reduced, likely due to a reduction in total energy intake via CHO reduction compared with the control group (Kephart et al., 2018). However, the ketogenic group also reduced leg muscle mass, which may have hindered adaptations and performance, if continued. Similar results were shown for a shorter, 6-week KD alongside CrossFit® training (Gregory et al., 2017) without any losses in lean BM. Conclusions from these studies are limited by low sample sizes and short duration of the dietary interventions. Male CrossFit® athletes have been shown to increase fat utilization at low exercise intensities (<65% maximal oxygen uptake) during incremental cycling following a 4-week KD, although the same shift in substrate utilization was not shown in female CrossFit® athletes (Durkalec-Michalski et al., 2019). Increased fat oxidation is an adaptation to KDs that may benefit low-intensity exercise, but this may come at a cost to metabolic flexibility via a reduction in CHO substrate pools and/or the ability to rapidly oxidize CHO (Burke & Hawley, 2018), which could have implications for high-intensity CrossFit® WODs. However, it remains unclear the extent to which CHO ingestion, via diet or supplementation, might influence CrossFit®-specific performance. Importantly, there is currently no evidence to support the use of Paleo or Zone diets for CrossFit® despite commonly being recommended among CrossFit® trainers (Maxwell et al., 2017). More studies are required to elucidate the importance of dietary CHO, or even the potential role of low-CHO, for CrossFit® performance.

Nutritional supplements are commonly employed by athletes to elicit marginal gains in performance (Peeling et al., 2018), although few are considered effective (Maughan et al., 2018) and any benefits are linked to their mechanisms of action. The intense and anaerobic nature of CrossFit®, with large increases in [Lac] and concomitant hydrogen ion accumulation, suggests that performance might be limited, in part, by muscle acidosis, meaning that supplements that increase buffering capacity, such as beta-alanine and SB, might improve CrossFit® performance (Carr et al., 2011; Saunders et al., 2017). Only one study has investigated the efficacy of buffering agents with chronic SB supplementation leading to improved performance during Benchmark FGB (Durkalec-Michalski et al., 2018). Further work should confirm the efficacy of SB for different WODs, and these data also suggest that supplements like beta-alanine may be ergogenic for CrossFit®. Caffeine has been shown to be effective for both aerobic and anaerobic exercise (Grgic et al., 2019), making it a compound of interest for CrossFit® athletes. However, 5 and 6 mg/kg acute caffeine supplementation did not improve CrossFit® performance (Fogaça et al., 2020; Stein et al., 2020). Neither study familiarized their participants to the exercise protocol, and, in fact, Stein et al. (2020) showed a significant learning effect from the first to the second session, which undermines any conclusions taken from this study. Nitrate supplementation might have performance effects via nitric oxide-mediated mechanisms on vasodilation, mitochondrial respiration, and calcium handling (Jones, 2014). Six days of potassium nitrate supplementation (4 mmol/day) improved peak power output during a 30-s Wingate cycle but did not improve more specific measures of CrossFit® performance, including Benchmark Grace (Kramer et al., 2016). The lack of an effect might be due to the use of potassium nitrate as opposed to a concentrated beetroot juice, and a recent meta-analysis showed daily doses <5 mmol were not ergogenic (Senefeld et al., 2020) and, as such, nitrate supplementation at higher doses for CrossFit® should not be discounted. Creatine is another effective supplement that, when combined with strength training, can lead to larger gains in muscle mass and strength (Kreider et al., 2017), making it an obvious avenue for research, particularly when considering the weightlifting aspect of CrossFit®. In addition, creatine has been shown to mitigate the interference effect observed in concurrent exercise (de Salles Painelli et al., 2014). Considering that many WODs combine both aerobic- and strength-oriented exercises, creatine could also be beneficial by minimizing residual fatigue between exercises. Despite this, no study has, so far, investigated the combination of creatine supplementation and CrossFit® training on strength and performance gains. Well-controlled supplementation studies involving these five supplements are an intriguing avenue for further work to determine their true merit for CrossFit® exercise.

Some studies have investigated whether antioxidants might benefit CrossFit® performance, although results remain inconclusive. The GTE has been purported to provide protection against reactive oxygen species and brain diseases, the latter effect of which may be due to increases in brain-derived neurotropic factor (Gomez-Pinilla & Nguyen, 2012). Six weeks of structured CrossFit® training did not improve maximal oxygen output during an incremental cycling test with or without GTE supplementation (Sadowska-Krepa et al., 2019); strangely, CrossFit®-specific performance was not evaluated in this study. However, CrossFit® training did lead to some improvements in antioxidant capacity and brain-derived neurotrophic factor with some marginal additional benefits from the GTE for antioxidant capacity (Sadowska-Krepa et al., 2019). Two days of epicatechin supplementation had no effect on 15.5 CrossFit® Open WOD performance (Schwarz et al., 2020), although caution is advised, as chronic supplementation of epicatechin alongside cycle training inhibited aerobic adaptations (Schwarz et al., 2018). Indeed, antioxidant supplementation for exercise remains controversial, and chronic supplementation may actually impair exercise adaptations (Pastor & Tur, 2019). It remains to be shown whether antioxidant supplementation can be effective during CrossFit® training or for CrossFit® WOD performance.

Practical Applications

Nutritional and supplement recommendations for CrossFit® based upon intervention studies are limited by a paucity of data and methodological shortcomings across studies. However, CrossFit®'s unique blend of combined strength, cardiovascular, and gymnastic activity and the homogenous physiological demands and responses to different WODs makes it possible to infer some recommendations for optimal performance, recovery, and adaptation (Figure 2). First, individuals should aim to meet their daily energy demand by considering the details pertaining to their training schedule (e.g., WODs included in their routine) to avoid chronic energy deficiency, which might have detrimental physiological and performance consequences associated with the Relative Energy Deficiency in Sport model (Mountjoy et al., 2018).

The average duration of individual CrossFit® WODs might not necessitate CHO supplementation, but individuals are likely to engage in repeated WODs during training and competition, and consecutive days of such high-intensity exercise might elicit glycogen depletion, rendering CHO an important macronutrient. Individuals involved in chronic CrossFit® training should aim to ingest 5–12 g/kg BM of CHO on the days around training and

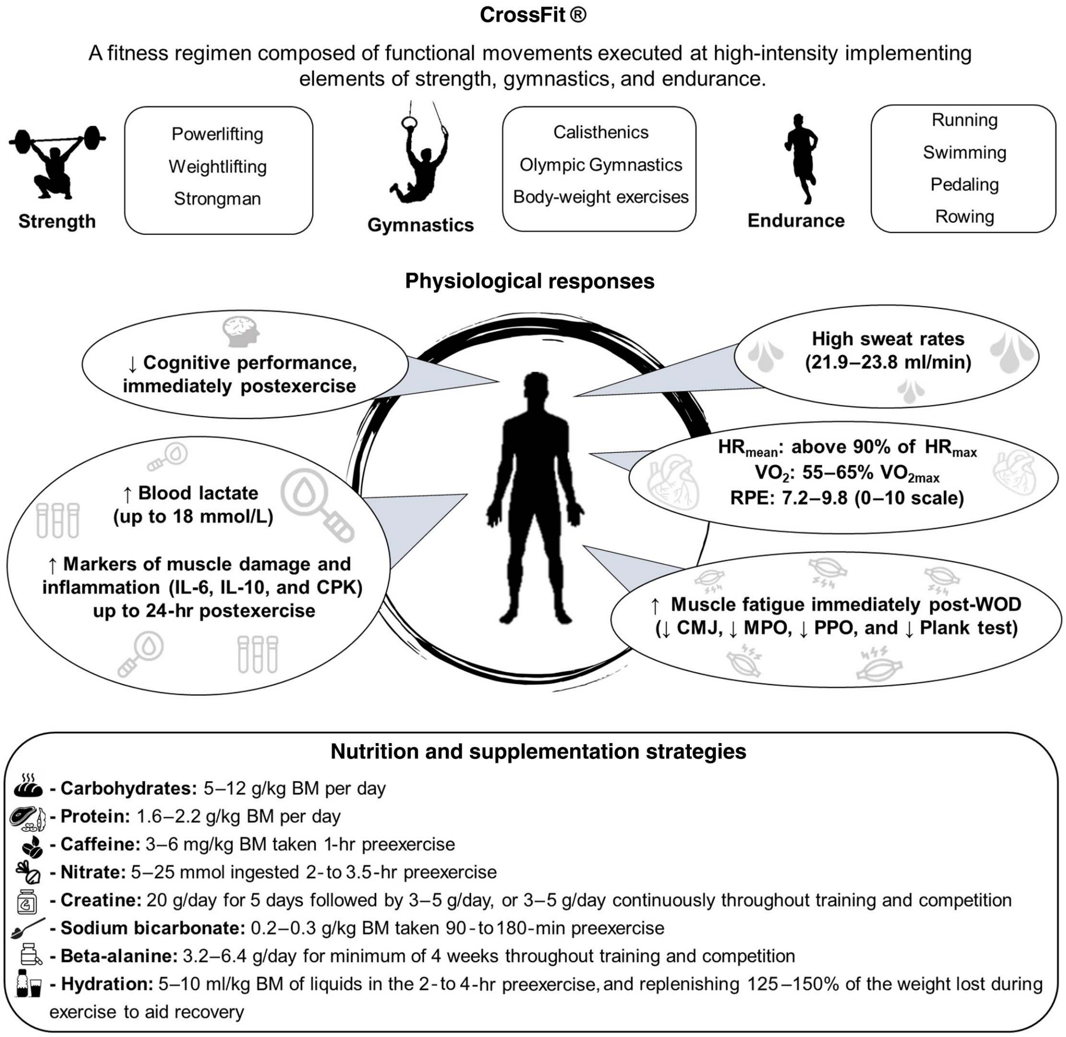

Figure 2 — Overview of CrossFit®, physiological responses to workouts, and nutritional guidelines to optimize performance and recovery. HR = heart rate; HR_{mean} = mean HR; HR_{max} = maximal HR; RPE = ratings of perceived exertion; CMJ = countermovement jump; BM = body mass; VO_2 = oxygen uptake; MPO = mean power output; PPO = peak power output; IL-6 = interleukin 6; IL-10 = interleukin 10; CPK = creatine phosphokinase; WOD = workout of the day.

competition (Thomas et al., 2016b). It must be acknowledged that those who wish to employ a low-CHO diet or KD might do so without any negative impact on their performance (Gregory et al., 2017; Kephart et al., 2018), although performance effects of a KD should be closely monitored. Individuals may also wish to periodize their CHO intake according to the specific goals of their macrocycle, mesocycle, and microcycles of training (Issurin, 2010); for example, low-CHO intake might enhance adaptation via upregulation of mitochondrial biogenesis-related signaling pathways (Impey et al., 2018) or help when the aim is to reduce body fat (Kephart et al., 2018). When engaging in weight- or fat-loss practice during training, sufficient protein ingestion is crucial to avoid muscle loss (Hector & Phillips, 2018). Similarly, as CrossFit® involves concurrent training and whole-body exercise, high protein intakes are recommended (Macnaughton et al., 2016), and protein will be particularly important during training blocks with increased strength training as occurs periodically during CrossFit® training. Thus, protein intake throughout training and competition should be approximately 1.6–2.2 g/kg BM per day to optimize recovery, promote gains, and stimulate muscle protein synthesis (Morton et al., 2018; Stokes et al., 2018). CrossFit® can elicit high sweat rates and losses (Cronin et al., 2016; Moreira et al., 2019), and athletes should aim to begin every training session in a euhydrated state, ingesting approximately 5–10 ml/kg of liquids in the 2- to 4-hr pre-WOD and replenishing 125–150% of any weight lost during exercise to aid recovery (Thomas et al., 2016b).

The International Olympic Committee suggests that only caffeine, creatine, nitrate, SB, and beta-alanine have good to strong evidence of efficacy in specific scenarios (Maughan et al., 2018). To date, only chronic SB has been shown to be effective for CrossFit® performance (Durkalec-Michalski et al., 2018), although other studies are limited by methodological shortcomings, and there is a lack of evidence for beta-alanine and creatine. Nonetheless, the characteristics of CrossFit® suggest that all these supplements might improve performance in their own right. For example, several WODs are 5–10 min in duration, the optimal timeframe for beta-alanine (Saunders et al., 2017) and SB (Heibel et al., 2018) to be effective, and exercise < 15 min in duration is also where nitrate supplementation is most effective (Senefeld et al., 2020). Caffeine is ergogenic for both strength and endurance exercise (Grgic et al., 2019), and creatine can improve workouts, leading to greater muscle gains throughout high-intensity training (Kreider et al., 2017) and mitigate the interference effect that occurs with concurrent exercise (de Salles Painelli et al., 2014). Suggested dosing strategies for these ergogenic aids are outlined in Figure 2 and are based upon general supplementation guidelines in the literature (Maughan et al., 2018), but research is desperately needed to confirm their efficacy, and some caution is advised, as some supplement combinations may not elicit additive effects and might actually hinder one another (Burke, 2017).

Perspectives for Research

This review has highlighted important methodological issues in study design that should be addressed in further work seeking to evaluate the effects of dietary or supplement interventions on CrossFit® performance. Most studies (approximately 70%) received a score of very low to moderate in the quality appraisal, although caution is advised even for those receiving a high score, as one such study failed to implement a familiarization to the main exercise protocol, which compromised the findings of the study (Stein et al., 2020). Thus, studies should ensure rigorous implementation of standardization procedures (e.g., dietary control) and, specifically, ensure familiarization to the exercise protocol(s) being undertaken regardless of CrossFit® experience, as a learning effect might occur. Work should address the typical error of WODs, including associated biological noise and biological variability (Swinton et al., 2018), to determine their suitability to detect changes in performance with nutritional interventions. More work with top-level CrossFit® athletes is required, and intervention studies should determine effects on CrossFit®-specific performance and not only on generic measures of exercise capacity (e.g., maximal oxygen uptake). The best dietary composition for optimal adaptation, injury-avoidance, and performance needs to be elucidated, and as mentioned, information is lacking as to the efficacy of ergogenic supplements to improve CrossFit®-specific performance; this is a fascinating avenue for investigation.

Conclusions

This systematic review showed that CrossFit® is a high-intensity sport with fairly homogenous anaerobic and aerobic characteristics, resulting in substantial metabolite accumulation and increased markers of muscle damage and muscle fatigue. Limited interventional data exist, most with moderate to very low quality, on dietary and supplementation strategies to optimize CrossFit® performance, precluding solid conclusions on their efficacy. Further high-quality work is required to elucidate the ideal dietary and supplementation strategies for optimal performance and recovery for CrossFit® athletes.

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