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RESEARCH

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The physical demands and physiological responses to CrossFit®: a scoping review with evidence gap map and meta-correlation

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Abstract

Background CrossFit® combines different types of activities (weightlifting, gymnastics, and cardiovascular training) that challenge aerobic and anaerobic pathways. Over the last few years, the scientific interest in CrossFit® has increased considerably. However, there have been no published reviews characterizing the physical demands and physiological responses to CrossFit®. The present study synthesizes current evidence on the physical demands and physiological responses to CrossFit®.

Methods The search was performed in three electronic databases (PubMed, Scopus, and Web of Science). Manuscripts related to the physical and physiological performance of adult CrossFit® participants written in English, Portuguese, and Spanish were retrieved for the analysis.

Results In addition, a meta-correlation was conducted to examine the predictors of CrossFit® performance. A total of 68 papers were included in the review. Physical and physiological markers differed between the different workouts analyzed. In addition, 48 to 72 h are needed to recover from a CrossFit® challenge. Specific tests that involve CrossFit® movements were more related to CrossFit® performance than non-specific.

Conclusion Although the characterization of CrossFit® is dependent on the workout examined, the benefits of muscle hypertrophy are aligned with the recent findings of concurrent training. The characterization of CrossFit® entire sessions and appropriate recovery strategies should be considered in future studies to help coaches manipulate and adjust the training load.

Keywords Physiology, Strength, Endurance, Concurrent training, Workout

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Background

CrossFit® includes the training and practice of weightlifting (e.g., snatch, clean, and jerk), gymnastics (e.g., handstand walk, ring muscle pull-up), and cardiovascular activities (e.g., running, rowing, cycling) [1, 2]. The practice of CrossFit® focuses on improving different components of fitness: cardiorespiratory, stamina, strength, flexibility, power, speed, coordination, agility, balance, and accuracy [3]. Different types of workouts are prescribed: Different types of workouts are prescribed: rounds for time (RFT), performing as many rounds as possible within a given time (AMRAP), and completing repetitions of exercises in a given number of minutes (every minute EMOM). For example, the "Angie" workout consists of completing 100 pull-ups, 100 push-ups, and 100 squats as quickly as possible; the "Chelsea" workout involves performing 5 pull-ups, 10 push-ups, and 15 squats every 60 s for 30 min; and the "Nate" workout involves the completion of as many rounds as possible in 20 min of muscle-ups, handstand push-ups, and kettlebell swing [4]. Given the varied nature of CrossFit®, there are many variables (number of repetitions, sets, load, rest between sets, movement, type of workout) that can influence the response to a stimulus and, consequently, have an impact on training adaptations [2, 5].

The organization of training sessions and the adjustments of training load are central to the modality since the CrossFit® Open is a competition that allows everyone to participate in three weeks of competition. Every week, an online challenge is proposed, and CrossFit® participants should perform, record, and submit their scores [6, 7]. Subsequently, the best twenty-five percent of CrossFit® Open results advanced to the subsequent phase of competition. Then, the top forty of each region (Europe, Africa, Asia, South America, North America East, North America West, and Oceania) advance to the semifinals. After the last phase, the top 40 athletes of both sexes are selected for the CrossFit® Games [6]. Coaches organize training sessions to optimize the three essential characteristics (i.e., weightlifting, gymnastics, and cardiovascular) that constitute the CrossFit® in order to prepare the participants for 'unknown and unknowable events [1, 2, 8]. At CrossFit® Games, athletes engage in unspecified events until right before the competition begins. The founder of CrossFit® recognized that methodological guidelines are empirical, but more evidence-based, measurable, observable, and repeatable data are needed [1].

Over the last decade, scientific interest has increased in CrossFit®, most notably in physical performance and physiology [9–11], injuries [12], psychology [13], and nutrition [14]. Reviews about CrossFit® often combine those who practice CrossFit® or are involved in functional or resistance training or those who are classified as healthy or sedentary participants, impacting the interpretation of physical, physiological, and performance data. Moreover, previous reviews focused on physical and physiological aspects [9–11] and did not examine the demands induced by each type of CrossFit® workout (i.e., AMRAP, RFT, EMOM). Given the variability of movements, training sessions, and, consequently, the metabolic demands imposed by CrossFit® workouts, a review focused on the physical and physiological outcomes of exclusively CrossFit® participants is lacking. Another challenge is which physical protocols should be applied to predict CrossFit® performance [9]. The present scoping review aims to summarize: (1) the physical and physiological demands in CrossFit®; (2) interpret the literature that explains different activity profiles within the CrossFit® context; (3) examine the association between CrossFit® performance and physical or physiological assessments; and (4) identify literature gaps and point suggestions for further research.

Methods

The current review followed the Cochrane instructions [15], PRISMA 2020 guidelines [16], and the respective extension for scoping reviews [16]. The protocol was developed by three expert elements and registered by an expert author on the Open Science Framework at https://doi.org/10.37766/inplasy2024.5.0063.

Eligibility criteria

Original studies published in peer-reviewed journals and written in English, Portuguese, and Spanish were included in the present review. There were no defined restrictions regarding the year of publication. The inclusion criteria were defined considering the Participants, Intervention, Comparator, Outcomes, and Study Design (PICOS) framework as follows: Participants – adult CrossFit® participants with previous training experience (minimal training experience or reported training practice had to be reported for inclusion); Intervention – any outcome, observation, intervention, or exposure associated with CrossFit® participation; Comparator – optional, other sporting activities, physical active; Outcomes – physical measures (for example, performance or body composition assessments); physiological outputs (such as maximal oxygen uptake, heart rate, rate of perceived exertion, hormonal levels); Study Design – no restrictions were applied to the type of studies included in the present review. Reviews and meta-analysis were not included.

Information sources, source strategy and selection process

Three databases were consulted (Pubmed, Scopus, and Web of Science) on 23rd February 2024 using the following search terms: (CrossFit OR "CrossFit Games" OR "workout of the day" OR "WOD$") AND ("training load" OR train* OR physiolog* OR perform* OR energ* OR metabol* OR nutrition* OR "body composition"). Originally, the initial purpose of this review was also to include CrossFit® studies that had a nutritional component; however, a decision was taken not to include these studies in the present review since there was a wealth of data available on physical and physiological parameters in CrossFit® participants. The inclusion of nutritional studies would have reduced the focus of the current review. After extracting the papers, they were combined into a reference management software (EndNoteTM 21.0, ClarivateTM). The omissions of duplicates followed a two-step process: (1) automatically removed and (2) manually checked to ensure that duplicates were removed with precision. One author (XXX) performed the entire screening process. Two authors (XXX/XX) examined the titles and abstracts to check if the studies met the eligibility criteria. The processes were then repeated for the full texts of the included papers. When discrepancies occurred, a third author (HS) was contacted to ensure concordance by consensus.

Data extraction and itsem

The two first authors (XXX/XX) organized a predefined template to collect relevant data about physical and physiological parameters. A third author (XX) confirmed the data extraction. The final summary of data comprised information on the different papers, considering the study's purpose and design. The data were categorized into the following topics: (1) characterization of physical (e.g., body fat percentage, lean body mass, weight lifted in CrossFit® movements) and physiological outcomes (e.g., VO_{2max}, heart rate, blood lactate); (2) assessments of the acute effects of different CrossFit® workouts on physical performance measurements; (3) data pertaining to the chronic effects of CrossFit® participation; (4) comparisons of CrossFit® participation with other types of training or no training; (5) interventional studies with participants of different competitive levels; (6) comparisons of different competitive levels in physical and physiological outcomes; (7) predictors of CrossFit® performance. Corresponding authors were individually contacted when the information was unavailable. In case the authors did not respond and the data were presented graphically, a specific software was used (GetData Graph Digitizer; http://www.getdata-graph-digitizer.com). This software has been shown to be accurate and precise [17] to extract mean and standard deviation from graphs.

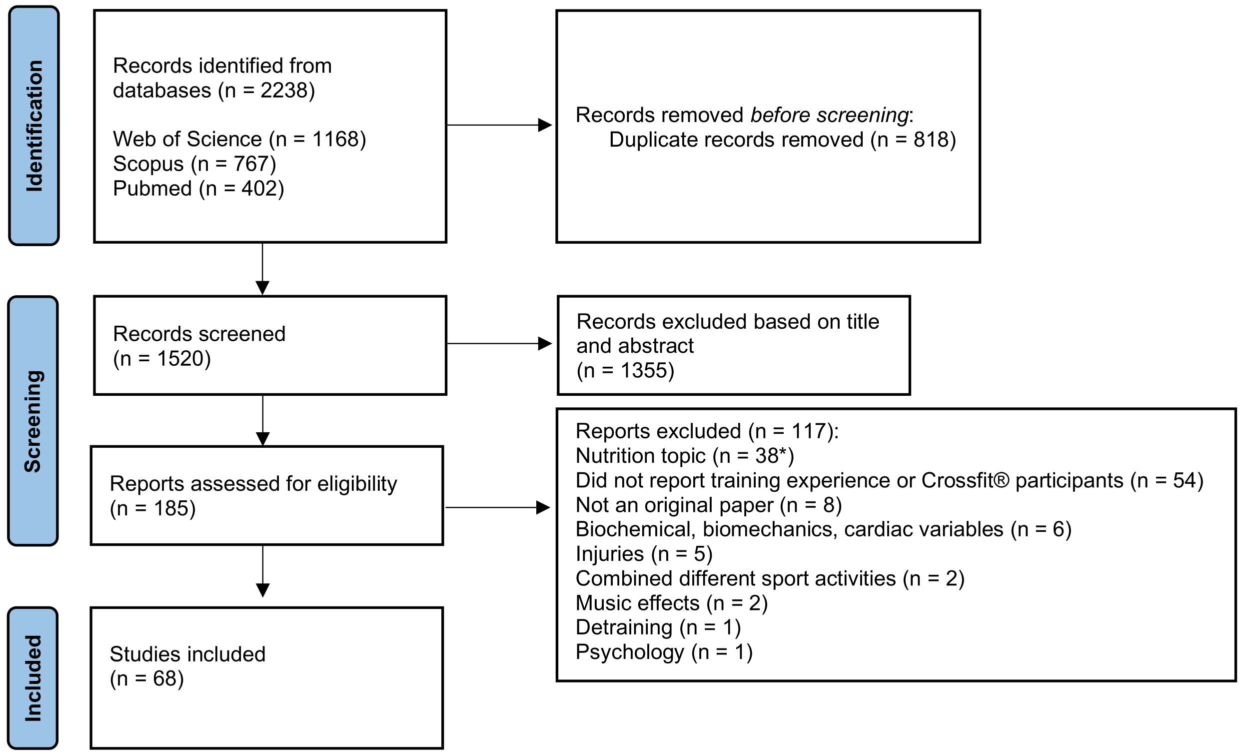
Statistical analysis

Data analyses were conducted using Comprehensive Meta-Analysis software (CMA, version 2.2.064, Biostat, NJ, USA). The main outcome was performance, which was divided considering three different groups: (1) global (overall performance or ranking), (2) studies focused on a challenge from a CrossFit® competition, only reported the challenge as workout of the day, rounds for time or as many rounds as possible, or combined different challenges, or (3) studies using particular workouts (e.g., Donkey Kong, Fran, Grace, Murph, Nancy). Different protocols were used to examine the relationship with CrossFit® performance and were classified according to the methodologies reported: specific from CrossFit® (e.g., snatch, bench press, squat) and non-specific (e.g., VO_{2max}, Wingate test). The statistical method for examining the relationship between two continuous variables over numerous studies is meta-correlation, also known as meta-analysis of r correlation coefficient. From each study, the coefficient of correlation and the number of participants were retrieved. The magnitude of correlation coefficients was interpreted as follows [18]: trivial ($r < 0.10$), small ($0.10 \leq r < 0.30$), moderate ($0.30 \leq r < 0.50$), large ($0.50 \leq r < 0.70$), very large ($0.70 \leq r < 0.90$), and nearly perfect ($r \geq 0.90$). The I^2 informed about the proportion of variance in correlation coefficients that was due to heterogeneity instead of chance. The cut-off values for I^2 values were interpreted as follows [19]: low ($I^2 < 25\%$), moderate ($25\% \geq I^2 > 75\%$), and high ($I^2 \geq 75\%$). Subgroup differences between different types of protocols were tested, and statistical significance was determined at a two-sided level of $p < 0.05$.

Results

Study identification and selection

The initial search was conducted in three databases, and 2238 records were detected. Of these, 818 were identified as duplicates, and once removed, 1520 papers were screened according to title and abstract. This process resulted in full-text screenings of 158 studies. Nine reasons were identified to exclude 117 studies: nutrition ($n = 38$), training experience (i.e., average or minimal experience) ($n = 54$), not an original paper ($n = 8$), not physical or physiological outputs ($n = 6$), papers about injuries ($n = 5$), combined different sports activities ($n = 2$), studies that examined music effects on performance ($n = 2$), detraining ($n = 1$), and psychological outputs ($n = 1$). Finally, 68 studies were included in the current review and were retrieved for the analysis, as shown in Fig. 1.



*Since the number of papers for physical and physiological parameters was considerable, authors will consider the relevant nutritional aspects of Crossfit® participants in a separate review.

Fig. 1 Prisma flow diagram of the study identification and selection to the present review

Study characteristics

Table 1 summarizes the primary information extracted from each study, the origin of the corresponding author, the inclusion criteria to be considered as a CrossFit® participant, sampling characteristics, aim, main methodologies or variables analyzed, as well as findings of each study [10, 20–86]. Twelve studies focused on the comparison between CrossFit® workouts or contrasted CrossFit® with types of training [22, 24, 25, 35, 41, 45, 50, 54, 63, 68, 74, 85]. Five studies distinguished participants of CrossFit® across different competitive levels [27, 31, 34, 43, 84]. Five studies focused on recovery [20, 38, 43, 71, 83] while seven papers centered on testing the data quality of protocols that can be useful for CrossFit® [32, 44, 46–48, 55, 75]. More than 50% of papers ($n = 38$) focused on the physical and physiological characterization of CrossFit® participants. Twenty-three (~34%) of the studies were organized by Brazilian authors, and American authors led 19 studies (~28%). Among European countries, Spanish authors were interested in research in CrossFit® ($n = 12$ manuscripts, ~18%) – Fig. 2, panel A. Data regarding the training experience in CrossFit® varied across the studies (Fig. 2, panel B). Most of the studies included participants with at least one year of experience ($n = 24$, ~35%), and the 6-month cut-off value to describe training experience was used in 15 studies (~22%). Three years of training experience was uniquely considered in four studies ($n = 4$).

Results of individual studies

As shown in Fig. 3 (panel A), regarding the evaluation of maximal oxygen uptake (i.e., VO_{2max}) during different workouts (i.e., Fran, Isabel, Cindy), the values varied within the same training workout and across metabolic challenges. Considering the Fran workout exclusively, the VO_{2max} reported in 20 participants with more than three years of practice was 49.2 ml·kg^{-1}·min^{-1} [20], whilst the value was substantially lower in 10 participants with one year of CrossFit® experience (29.1 ml·kg^{-1}·min^{-1}) [85]. The VO_{2max} of other metabolic challenges (i.e., Isabel and Cindy) was also substantially different than the values obtained in response to the Fran Workout [21, 85]. The overall mean of maximal heart combining the data points was 184 beats per minute, with individual values of each study ranging from 177 beats per minute on an as many rounds as possible workout [87] to 189 on rounds

Table 1 Summary of sampling, aim, methodologies and results of studies that investigated physical and physiological dimensions of CrossFit® participants

Study	Country of contact author	Inclusion criteria (CrossFit® practice)	Sample characteristics	Aim	Main methodologies/ variables extracted	Main results	Main topic
Rios et al. [20]	Portugal	≥ 3 yrs	*N* = 14 males, *N* = 6 females (age: 29.6 ± 4.0 yrs, training experience: 5.9 ± 1.1 yrs)	Describe the physical and physiological impact of Fran workout and recovery period	VO_{2max}, heart rate, lactate, RPE, jumping, force, velocity	After 24 h of the CrossFit® workout, the values of jumping outputs and force are ↓ compared to the baseline	Physical and physiological characterization; Physical – recovery
Rios et al. [21]	Portugal	≥ 3 yrs	*N* = 14 males (age: 28.3 ± 5.4 yrs, training experience: 5.6 ± 1.8 yrs)	Describe the physiological impact of Isabel workout and recovery period	VO_{2max}, RER, HR, lactate, RPE	↑ RER after 5 min to finish the workout ↓ HR decreased from 177 to 128 bpm 5 min after to stop the exercise	Physiological characterization
Carvalho et al. [22]	Brazil	≥ 2 months	*N* = 7 males, *N* = 22 females (age: 29.7 ± 5.2 yrs, training experience: NR)	Compare two different types of training (running vs. CrossFit®) on anthropometric characteristics, cardiorespiratory fitness, sleep quality and lipids parameters	Pittsburgh Sleep Quality Index, cardiorespiratory fitness and lipid profile	↓ volume of training in running training ↑ VO_{2max} running training	Comparison between workouts
Santos et al. [23]	Brazil	> 6 months	*N* = 21 males (age: 26.4 ± 4.1 yrs, training experience: 2.1 ± 4.1 yrs)	Compare physiological outputs on CrossFit® training and high intensity continuous training	HR, lactate, RPE, RPD	↑ HR_{max}, lactate, RPE and RPD in CrossFit® training ↔ HR_{mean} in both trainings	Comparison between workouts
Rios et al. [24]	Portugal	≥ 3 yrs	*N* = 16 males, *N* = 4 females (age: 26.0 ± 5.0 yrs, training experience: 5.8 ± 2.2 yrs)	Characterize the Fran workout according to metabolic pathways	VO_{2max}, HR, RPE lactate	During Fran: ↓ aerobic (29–52%) and anaerobic alactic (23–30%) ↑ lactate (18–48%)	Physiological characterization
Pearson et al. [25]	U.S	> 1 yr	*N* = 13 males, *N* = 8 females (age: 18 – 30 yrs, training experience: NR)	Compare aerobic capacity, metabolic response, mitochondrial capacity, large vessel function and between CrossFit® participants and control group	VO_{2max}, body fat, lactate, mitochondrial and vascular characteristics	↑ VO_{2max} in CrossFit® participants ↑ post lactate exercise in CrossFit® participants ↓ body fat (CrossFit® group: 18.6 ± 3.8%, control group: 30.3 ± 8.4) CrossFit® participation ↑ mitochondrial and vascular function	Comparison between workouts

Table 1 (continued)

Study	Country of contact author	Inclusion criteria (CrossFit® practice)	Sample characteristics	Aim	Main methodologies/ variables extracted	Main results	Main topic
Párraga-Montilla et al. [26]	Spain	>6 months	N = 72 males, N = 18 female (age males: 33.2 ± 6.0 yrs, age females: 30.1 ± 6.9 yrs, training experience: NR)	Describe neuromuscular characteristics considering the force velocity profile	Squat jump, countermovement jump, drop jump	↑ velocity than force which highlights deficits in force–velocity profile	Physical characterization
Meier et al. [27]	Germany	NR	N = 27 males and females (age: 30.9 ± 4.2 yrs, training experience: 1.3 ± 1.1 yrs)	Examine differences on physiological parameters using athletes of contrasting experience levels	HR	Variation in maximal heart rate within CrossFit® session ↔ no differences in HR_{mean} and HR_{mean} between contrasting groups experience	Comparison by competitive level
Manrique et al. [28]	Colombia	>1 yr	N = 30 males (age: 26.6 ± 5.2 yrs, training experience: NR)	Compare physical performance of CrossFit® athletes of contrasting experience athletes	Body fat, RM squat, RM bench press	↔ body fat percentage between competitive levels RM bench press and squat ↑ in elite group	Comparison by competitive level
Mangine et al. [29]	U.S	Participation in CrossFit® Open	N = 80 males, N = 80 females (age: NR, training experience: NR)	Test the impact of sex and rank on pacing strategy during the 2020 CrossFit® Open	Repetition per test, repetition per minute, failed repetitions, break times, transition times	Top male participants were 17.5% faster during tests 1, 3 and 5 Top female participants were 9.5% faster in tests 1 and 3 Top 10% athletes were faster Males keep their pace during resistance exercises in comparison to female participants	Physical characterization

Table 1 (continued)

Study	Country of contact author	Inclusion criteria (CrossFit® practice)	Sample characteristics	Aim	Main methodologies/variables extracted	Main results	Main topic
Mangine et al. [30]	U.S	Participation in CrossFit® Open	*N* = 476.346 males, *N* = 216.261 females (age: NR, training experience: NR)	Creating percentiles for CrossFit® Open, examined differences between male and females	Workout performances	Differences between sexes were noted for most of the workouts (~ 93%) Workouts scored by repetitions completed—↑ repetitions in 18 workouts among males, ↑ repetitions in 6 workouts among females Workouts assessed by time – males faster in 10 workouts whilst females were faster in 6 workouts Males lifted ↑ load in three workouts	Physical characterization
Mangine et al. [31]	U.S	Participation in CrossFit® Open	*N* = 550.00 males, *N* = 550.000 females (age: NR, training experience: NR)	Test performance variation and sex variation in workouts and subsequent impact on ranking	Workout performances	Across the time performance tend to improve however, negligible changes in ranking position were noted	Physical characterization
Linhares et al. [32]	Brazil	NR	*N* = 35 males (age: 31.0 ± 5.2 yrs, training experience: 3.2 ± 1.6 yrs)	Test the association between strength and power with power clean movement	Isometric mid-thigh pull, countermovement jump, RM power clean	Maximal isometric mid-thigh pull was positively related RM power clean ($r = .51$, $p < 0.05$) Lower limbs power output and rate of force development were weakly related to the power clean performance	Testing
da Silveira Castanheira et al. [33]	Brazil	> 2 yrs	*N* = 16 males and females (age: 31.0 ± 6.8 yrs, training experience: 2.8 ± 0.8 yrs)	Examine physical and physiological performance across three months of CrossFit® training	Sleep quality, pain score, recovery index, countermovement jump, HR variability	↔ sleep quality, countermovement jump and RMSSD Fluctuations on pain score were found	Physical and physiological characterization
Brito et al. [34]	Brazil	> 1 yr	*N* = 32 males and females (age and training experience reported by competitive level)	Test the impact of FRAN WOD on psychophysiological outputs in different competitive levels	Cognition parameters, HR, blood pressure	Changes in cognitive levels were noted in all competitive groups ↔ HR and blood pressure on post-test of elite and beginner participants	Comparison by competitive level

Table 1 (continued)

Study	Country of contact author	Inclusion criteria (CrossFit® practice)	Sample characteristics	Aim	Main methodologies/variables extracted	Main results	Main topic
Barreto et al. [35]	Brazil	> 1 yr	*N* = 9 males (age: 29.6 ± 3.5 yrs, training experience: NR)	Test the impact of different workouts in heart rate and blood pressure	HR variability, blood pressure	After workouts ↓ parasympathetic indexes and ↑ sympathetic indexes After WODs ↓ in systolic blood pressure	Comparison between workouts
Schlegel et al. [36]	Czech Republic	Qualifying for the CrossFit Games®	*N* = 40 males and females (age males: 27.2 ± 3.7 yrs, age females: 27.8 ± 5.1 yrs, training experience: NR)	Compare sex performance in CrossFit® competitions	Workout performances	In most of events, males attained better performance than females (difference ranged from 0.1 to 33.1%) The biggest difference was in RM of snatch	Physical characterization
Menargues et al. [37]	Spain	> 2 yrs	*N* = 19 males, *N* = 8 females (age males: 39 yrs, age females: 28 yrs, training experience: NR)	Describe anthropometric profile of athletes and the impact on physical performance	Body composition (anthropometry), workout performances	A positive and a significant relationship between muscle mass and total load performed (r = .876) in Total CrossFit® workout	Physical characterization
Martínez-Gomez et al. [38]	Spain	> 1 yr	*N* = 15 males (age: 29.0 ± 8.0 yrs)	Compare different methods of recovery (cycling, neuromuscular electrical stimulation, control) in CrossFit® participants	RPE, delayed-onset muscle soreness, HR blood lactate, muscle saturation, countermovement jump	↓ RPE in neuromuscular compared to control group Negligible differences were found between the remaining protocols	Physical and physiology – recovery
Mangine et al. [39]	U.S	> 1 yr	19 male participants (age: 31.0 ± 6.8 yrs, training experience: NR)	Test the association between body composition and FRAN performance	Body composition (dual-energy X-ray absorptiometry)	Body composition was related to performance in male and females in FRAN performance The association is also modulated by competitive level and rank	Physical characterization
Mangine et al. [40]	U.S	> 1 yr	220 male CrossFit® Open athletes (age: 28.5 ± 4.4 yrs, training experience: NR)	Test the influence of previous performance on 2020 CrossFit® Open results	Workout performances	Previous ranking and regional appearances were associated with overall and weekly subsequent performance in 2020 CrossFit® Open	Physical characterization

Table 1 (continued)

Study	Country of contact author	Inclusion criteria (CrossFit® practice)	Sample characteristics	Aim	Main methodologies/variables extracted	Main results	Main topic
Forte et al. [41]	Brazil	>6 months	*N* = 11 males, *N* = 12 females (age: 25.9 ± 3.6 yrs, training experience: NR)	Compare the physiological performance in two different workouts (Cindy and Open Access 18.4)	HR, blood pressure, lactate	Physiological differences were noted between Cindy and Open Access 18.4 workouts Heart rate ↑ Cindy and Open Access 18.4 Lactate ↑ after exercise in Open Access 18.4 in comparison to Cindy and differences were maintained after 30 min	Compare different workouts
Dias et al. [42]	Brazil	>6 months	*N* = 15 males (age: 26.0 ± 6.5 yrs, training experience: 1.2 ± 0.3 yrs)	Examine acute training load in CrossFit® sessions	HR, RPE	HR ↑ mobility and workout segments HR was, on average, 65.1 ± 5.4% HR_{max} RPE and HR ↑ increased in each segment of training	Physical characterization
Sousa-Neto et al. [43]	Brazil	>6 months	*N* = 8 males (age: 28.4 ± 6.4 yrs, training experience: NR)	Determine the recovery time of Karen workout	Countermovement jump, CK, PRS	↑ CK 24-h after the baseline ↔ countermovement jump ↓ PRS decreased 24 h after exercise and ↑ in subsequent hours	Physical recovery
Conde et al. [44]	Brazil	> 10 months	*N* = 7 females (age: 18–40 yrs, training experience: 1.9 ± 1.2 yrs)	Examine the sensitivity (changing detection) of physical tests and subjective scale of recovery	Perception of recovery (subjective scale), Karen performance, repetitions until failure (squat, bench press), countermovement jump, tapping test	Two microcycles were examined (aerobic and strength): in strength microcyle the squat resistance test was associated with training load (*r* = 0.76). In opposition, any physical test was associated with training load in aerobic microcyle	Testing

Table 1 (continued)

Study	Country of contact author	Inclusion criteria (CrossFit® practice)	Sample characteristics	Aim	Main methodologies/ variables extracted	Main results	Main topic
Toledo et al. [45]	U.S	> 1 yr	N = 13 males, N = 10 females (age: 26.5 ± 4.3 yrs, training experience: 2.0 ± 0.6 yrs)	Compare physiological outputs in two different types of training (i.e. as many rounds as possible and rounds for time)	HR, blood lactate, RPE	Among females: ↔ HR_{max} and lactate in both type of workouts ↑ RPE in rounds for time workout Among males: ↔ HR_{max} in both type of workouts ↑ blood lactate and RPE in rounds for time workout	Compare different workouts
Tibana et al. [46]	Brazil	> 6 months	N = 11 males, N = 6 females	Assessed the relationship between physical performance and CrossFit® Open 2020	Body composition (dual-energy X-ray absorptiometry), VO_{2max}, strength, power, muscular endurance	CrossFit® specific tests (strength, endurance) had ↑ association with performance Negligible associations between performance, body fat and cardiorespiratory fitness were noted	Physical characterization
Schlegel et al. [47]	Czech Republic	Best results in the Czech CrossFit® Open ranking	N = 20 males (age: 28.5 years yrs, training experience: 5.1 yrs)	Test the relationship between strength and endurance with CrossFit® Open	Questionnaire about current performance	Olympic movements (snatch, clean and jerk) were associated with classification in the CrossFit® Open	Testing
Ponce-Garcia et al. [48]	Spain	> 1 yr	N = 19 (age: 28.6 ± 6.6 yrs, training experience: NR)	Compare laboratory and field protocols	Anaerobic squat tests (60% of body weight; 70% of body weight), repeated jump test, assault bike test, Wingate anaerobic test	Compared to Wingate anaerobic test, a systematic bias of field test ranged from -110 to 464 watts Differences between protocols were significant	Testing
Pena et al. [49]	Spain	> 2 yrs	N = 10 males (age: 28.8 ± 3.5 yrs, training experience: NR)	Test the relationship between anthropometric, physical fitness with performance	Anthropometric measurements and fitness tests	CrossFit® performance was associated with snatch load (corresponding to the ↑ mean power) The combination of different physical tests also explained 72% of CrossFit® performance	Physical characterization
Mota et al. [50]	Brazil	> 1 yr	N = 10 males (age: 30.0 ± 6.6 yrs, training experience: NR)	Analyze the effects of two CrossFit® protocols on glycemia level	Glycemia level	↑ glycemia levels in Diana and Cindy workouts compared to pre-test ↔ glycemia in both workouts	Compare different workouts

Table 1 (continued)

Study	Country of contact author	Inclusion criteria (CrossFit® practice)	Sample characteristics	Aim	Main methodologies/variables extracted	Main results	Main topic
Meier et al. [51]	Germany	NR	*N* = 66 male, *N* = 96 females (age: 32.6 ± 8.2 yrs, training experience: 3.4 ± 1.9 yrs)	Define athletic patterns for American and German CrossFit® athletes	Questionnaire about benchmark profile	Significant correlations were found between the power lift and Olympic lifts ↑ values of explanation between RM squat and Olympic lifts (snatch, clean and jerk)	Physical characterization
Mangine et al. [52]	U.S	> 6 months	*N* = 5 males, *N* = 6 females (age males: 34.4 ± 3.8 yrs, age females: 35.2 ± 6.3 yrs, training experience: 1–5 yrs)	Evaluate pacing strategies in CrossFit® athletes and the impact on performance	Workouts performance and pacing variables (repetition rate)	Average rate of round predicted ≥ 89% of performance in difference workouts Other variables were determinant to explain performance in different workouts: competitive level, rest between thrusters and burpees	Physical characterization
Leitão et al. [53]	Portugal	> 3 yrs	*N* = 15 males (age: 24.0 ± 4.2 yrs, training experience: NR)	Determine the physical and physiological impact of performance in FRAN WORD	RM pull-ups, RM and thrusters, row test, FRAN performance	↑ blood lactate, HR, RPE in 2 km rowing and maximal repetition of thrusters FRAN performance was associated with RM of thrusters and pull-ups, RM thrusters, 2 km rowing	Physical and physiological characterization
Fernando et al. [54]	Brazil	> 6 months	*N* = 16 males (age: 29.0 ± 8.5 yrs, training experience: 1.3 ± 0.9 yrs	Compared two different types of training (CrossFit® vs. Cross-training)	Body composition (anthropometry) and physical tests	No differences were found between groups	Compare different workouts
Fernández-Lazaro et al. [55]	Spain	> 1 yr	*N* = 10 males (age: 38.4 ± 3.8 yrs, training experience: NR)	Examine the effects of elevation training mask (12 weeks)	CrossFit® performance, lactate dehydrogenase, CK, myoglobin, testosterone, cortisol	No differences between groups were found on performance, metabolic markers and hormones	Testing
Bustos-Viviescas et al. [56]	Colombia	> 10 months	*N* = 4 males, *N* = 4 females	Test the association between body fat and physical performance	Body composition (anthropometry), cardiorespiratory fitness	Robust associations between body fat percentage and cardiorespiratory fitness were found in males (r = -0.94), females (r = -0.95) and whole sample (r = -0.87)	Physical characterization

Table 1 (continued)

Study	Country of contact author	Inclusion criteria (CrossFit® practice)	Sample characteristics	Aim	Main methodologies/variables extracted	Main results	Main topic
Pritchard et al. [57]	New Zeeland	Participation on 2018 Crossfit® games	N = 33 males, N = 39 females	Describe tapering practices in Crossfit® athletes	Online survey	Most of the athletes (~ 99%) tapered preceding important competitions 90% of athletes ↓ training duration Training volume ↓ ~ 41% Strength and conditioning volume peaked, on average, 5 weeks before the competition	Physical characterization
Martínez-Gomes et al. [58]	Spain	> 1 yr	N = 15 males (age: 35.0 ± 9.0 yrs, training experience: 3.3 ± 2.2 yrs)	Identify the main predictors of CrossFit® performance	Physical (squat, bench press, jumping), laboratory tests (treadmill and Wingate), CrossFit® performance	The associations between CrossFit® performance and jumping performance, Wingate test, relative strength (bench press and squat), VO_{2max} and speed were large (r value ranged from 0.58–0.75) Jumping performance and VO_{2max} explained ↑ variance of CrossFit® performance	Physical and physiological characterization
Mangine et al. [59]	U.S	> 1 yr	N = 8 males, N = 8 females (age: 30.7 ± 6.9 yrs, training experience: > 2 yrs)	Identify the main predictors of CrossFit® Open performance	Resting energy expenditure, hormone parameters, body composition (4-compartment model), muscle morphology (ultrasound), cardiorespiratory fitness, isometric strength, Crossfit® Open performance	Body fat percentage was determinant to explain performance in three workouts (R^2 ranged from 0.55 to 0.89) Other predictors also explained considerably the CrossFit® performance: training experience, muscle morphology, cardiorespiratory parameters and rate of strength development	Physical and physiological characterization

Table 1 (continued)

Study	Country of contact author	Inclusion criteria (CrossFit® practice)	Sample characteristics	Aim	Main methodologies/variables extracted	Main results	Main topic
Mangine et al. [60]	U.S	> 2 yrs	*N* = 16 males and females (experienced group – age: 27.8 ± 4.2 years, training experience: 6.4 ± 5.6 yrs; recreational group: 33.5 ± 8.1 yrs, training experience: 3.3 ± 1.7 yrs)	Examine differences in anthropometric, hormonal and physiological of participants in contrasting competitive levels (advanced, recreational, control)	Resting energy expenditure, body composition, muscle morphology, aerobic condition, strength, blood samples	Advanced participants ↓ body fat percentage, ↑ muscle morphology, strength, aerobic capacity and 3-min maximal test ↔ recreational and control groups have identical characteristics	Comparison by competitive level
Gomez-Landero et al. [61]	Spain	> 2 yrs	*N* = 15 males (age: 30.5 ± 5.5 yrs, training experience: NR)	Test the association between morphological variables and performance	Skinfolds, RM squat, maximal, RM bench press, maximal pull-ups, sit-ups (60 s), countermovement jump, shuttle run test (VO_{2max}), CrossFit® performance (Fran and Donkey Kong)	Donkey Kong was related with VO_{2max} (r = -0.68), suprailiac skinfold (r = 0.71) and sit-ups (r = -0.56) Fran workout was related with squat performance (r = -0.53)	Physical characterization
Gomes et al. [62]	Brazil	> 3 months	*N* = 23 (age: 31.0 ± 1.0 yrs, training experience – novel: 0.5 ± 0.1 yrs, experienced: 2.4 ± 0.2 yrs)	Examine the acute impact of CINDY workout regarding muscular markers, inflammatory system and stress	White blood cell, CK, cortisol, lactate	Post exercise noted ↑ white blood cells, lymphocyte, cortisol in experience athletes ↔ CK levels were found in different competitive levels	Physiological characterization
Faelli et al. [63]	Italy	1 yr	*N* = 20 males (age – CrossFit® group: 26.4 ± 3.4 yrs, RT: 26.3 ± 3.6 yrs, training experience: 1 yr)	Compare acute and catabolic markers in two different types of training (CrossFit® vs. resistance training)	Cortisol, interleukin 1-beta, uric acid	Acute effects of CrossFit® training ↑ cortisol levels whilst, in resistance training the cortisol levels ↓ Chronic effects ↓ cortisol levels in CrossFit® training and negligible changes were noted for resistance training IL-1β ↓ after CrossFit® and resistance training (acute effects) Uric acid ↑ after CrossFit® and resistance training (acute effects)	Compare different workouts

Table 1 (continued)

Study	Country of contact author	Inclusion criteria (CrossFit® practice)	Sample characteristics	Aim	Main methodologies/ variables extracted	Main results	Main topic
Dexheimer et al. [64]	U.S	> 1 yr	*N* = 17 males (age: 29.5 ± 5.6 yrs, training experience: NR)	Test the impact of muscular strength in workout performance	RM back squat, strict shoulder press, deadlift, workouts performance. The combination of RM was defined as total body strength	Total boy strength explained 62% of variance on 30 clean and jerks time performance No significant correlations between workouts and total body strength were found	Physical characterization
Cavedon et al. [65]	Italy	> 1 yr	*N* = 24 males (age: 28.2 ± 3.4 yrs, training experience – high volume: 2.5 ± 0.8 yrs, low volume: 1.8 ± 0.9 yrs)	Compare the effects of body composition and performance considering distinct volumes of training	Body composition (dual-energy X-ray absorptiometry), Fran performance	↑ volume of training was associated with ↑ Fran performance ↑ volume of training group had ↑ bone mineral density, lean soft mass and ↓ fat mass percentage	Physical characterization
Carreker et al. [66]	U.S	> 6 months	*N* = 11 (age: 27.2 ± 3.3 yrs, training experience: 3.9 ± 2.6 yrs)	Test the physiological predictors of Murph challenge	Body composition (dual-energy X-ray absorptiometry), upper and lower body strength, body endurance, anaerobic power, VO_{2nax}, Murph performance	Body fat percentage was associated with Murph performance ($r = 0.72$) Run time (during Murph) was associated with relative anaerobic power ($r = -0.63$) and ↓ anaerobic fatigue ($r = 0.64$)	Physical characterization
Cardenosa et al. [67]	Spain	> 1 yr	*N* = 10 males (age: 30.4 ± 5.4 yrs, training experience: NR)	Examine the effects of CrossFit® participation (6 weeks) on physical performance, body composition and biochemical parameters	Physical performance, biochemical parameters	↔ in physical performance after 6-weeks of CrossFit® training ↑ fat oxidation rate (63%) ↓ carbohydrate oxidation (27%) ↑ lactate dehydrogenase (27%)	Physical and physiological characterization

Table 1 (continued)

Study	Country of contact author	Inclusion criteria (CrossFit® practice)	Sample characteristics	Aim	Main methodologies/variables extracted	Main results	Main topic
Timón et al. [68]	Spain	> 1 yr	*N* = 12 (age: 30.0 ± 5.4 yrs, training experience: NR)	Test physical performance and biochemical parameters after two different types of training (e.g. as many rounds as possible, rounds for time) and to examine recovery time 24 and 48 h after these two workouts	Lactate, RPE, HR, two types of workout performances (as many rounds as possible, rounds for time)	Physiological different between the type of workouts were found: Rounds for time ↑ blood lactate, heart rate, blood glucose compared to as many rounds as possible After workout sessions ↑ hepatic transaminases, CK, blood glucose and ↓ physical performance After 48 h, values returned to baseline	Compare different workouts
Poderoso et al. [69]	Brazil	> 6 months	*N* = 17 males, *N* = 12 females (age: 35.3 ± 10.4 yrs, training experience – males: 0.8 ± 0.2 yrs, females: 0.7 ± 0.2 yrs)	Examine the chronic effects (over six months) in CrossFit® practice on hormonal parameters	Testosterone, cortisol, testosterone:cortisol ratio	Testosterone ↑ after 6 months and values ↑ among males in comparison to females Cortisol ↓ all time points in comparison to initial levels ↓ testosterone:cortisol ratio in females compared to males	Physiological characterization
Martínez-Gomes et al. [70]	Spain	1 yr	*N* = 23 males (age: 33.0 ± 7.0 yrs, training experience: NR)	Test the association between CrossFit® performance and back squat exercise (i.e. strength and power)	Sum of scores in specific WODs, peak and mean power (squat), RM squat	Robust correlations (*r* = 0.47 o 0.69) were found between squat variables analyzed and CrossFit® performance ↑ correlations were noted for absolute and relative RM, peak and mean adjusted for body weight	Physical characterization
Feito et al. [71]	U.S	> 2 yrs	*N* = 15 males, *N* = 14 females (age: 28.6 ± 5.7 yrs, training experience: NR	Assess the physiological response after Wingate trials with short and active recovery periods	Four Wingate trials, VO_{2max}, respiratory exchange ratio, rate of perceived effort	The explanation of 15 min as many rounds as possible ↑ as the participants progress from the first to the third trial. of Wingate test	Physiology – recovery

Table 1 (continued)

Study	Country of contact author	Inclusion criteria (CrossFit® practice)	Sample characteristics	Aim	Main methodologies/variables extracted	Main results	Main topic
Dexheimer et al. [72]	U.S	1 yr	*N* = 12 males, *N* = 5 females (age: 28.0 ± 5.0 yrs, training experience – males: 4.1 ± 2.7 yrs, females: 2.5 ± 1.5 yrs)	Determine the importance of physiological indicators on CrossFit® performance	VO_{2max}, 3-min maximal test, Wingate test, CrossFit® total, CrossFit® benchmarks	Back squat explained 42% of FRAN performance VO_{2max} explained 68% of Nancy performance Peak power (derived from Wingate) explained 57% of CrossFit® total performance	Physiological characterization
De Oliveira et al. [73]	Brazil	> 3 months	10 male and 6 female CrossFit® participants (age: 32.1 ± 6.4 yrs, training experience: 2.4—20 yrs)	Describe the HR variability among CrossFit® athletes	HR variability	Sympathetic activity was frequent in CrossFit® participants	Physiological characterization
Barbieri et al. [74]	Brazil	NR	4 male and 4 female CrossFit® participants (age: 28.6 ± 4.3 yrs, training experience: 1.6 ± 0.7 yrs)	Compare different types of training (CrossFit®, recreational trained)	Body composition (skinfolds), cardiorespiratory test	CrossFit® ↑ lean mass than resistance training CrossFit® ↓ second ventilatory threshold, power of first and second ventilatory threshold than resistance training Heart rate recovery ↓ CrossFit® group than resistance training	Compare different workouts
Tibana et al. [75]	Brazil	> 6 months	8 male CrossFit® participants (age: 28.1 ± 5.4 yrs, training experience: 3.8 ± 1.4 yrs)	Examine the adequacy of rate of perceived exertion on the control of the intensity	RPE, HR, lactate, number of repetitions	The RPE and lactate during the all-out sessions were ↑ than the RPE6 ↔ heart rate area under the curve and RPE6 sessions RPE and lactate were significantly correlated RPE and heart rate were not related	Testing

Table 1 (continued)

Study	Country of contact author	Inclusion criteria (CrossFit® practice)	Sample characteristics	Aim	Main methodologies/variables extracted	Main results	Main topic
Tibana et al. [76]	Brazil	>6 months	9 healthy male CrossFit® participants (age: 27.7 ± 3.2 yrs, training experience: NR)	Test the acute and effects of CrossFit® sections with different characteristics on physiological parameters	Lactate, RPE, HR	Shorter sessions ↑ lactate (15.9 ± 2.2 $mmol{\cdot}L^{-1}{\cdot}min^{-1}$) compared to longer sessions (12.6 ± 2.6 $mmol{\cdot}L^{-1}{\cdot}min^{-1}$) Lactate ↑ recovery period for both training sessions in comparison to pre-exercise HR ↔ in both type of sessions RPE was ↔ in both type of sessions after exercise	Physical and physiological characterization
Tibana et al. [77]	Brazil	>6 months	30 male CrossFit® participants (age: 27.2 ± 33.0 yrs, training experience: 27.1 ± 4.1 yrs)	Validate the perceived rate exertion tool during CrossFit® sections	RPE, HR	↑ correlation between Edwards-TRIMP and RPE in all time frames (0, 10, 20 and 30-min post-exercise)	Testing
Tibana et al. [78]	Brazil	>6 months	22 male CrossFit® participants (age: 29.6 ± 4.4 yrs; training experience: 2.4 ± 0.9 yrs)	Examine the relationship between two three different movements – squat (back, front), snatch and clean	Strength (back squat, front squat, snatch, clean)	↑ snatch, clean ↑ back squat, front squat	Physical characterization
Serafini et al. [79]	U.S	Athletic profile in Crossfit® Games	3000 male and female participants	Determine the utility of self-reported variables distinguished the 2016 CrossFit® profile	Self-reported performance measures, performance CrossFit® Open 2016	Successful athletes were better in physical condition and skill Lower-level athletes should focus on the develop strength and power after attaining a sufficient proficiency of sport-specific skills	Physical characterization

Table 1 (continued)

Study	Country of contact author	Inclusion criteria (CrossFit® practice)	Sample characteristics	Aim	Main methodologies/variables extracted	Main results	Main topic
Mangine et al. [80]	U.S	> 2 yrs	5 male CrossFit® participants (age: 34.4 ± 3.8 yrs, training experience: NR)	Examine metabolic indicators across 5-weeks of CrossFit® international competition	Testosterone, cortisol, testosterone:cortisol ratio	Testosterone ↑ immediately after training from week 2 to week 5 The ↑ on testosterone were also noted 60 min after the session on week 3 and week 5 ↑ concentrations of cortisol were noted immediately and 30 min after training in all weeks	Physiological characterization
Mangine et al. [81]	U.S	Athletic profile in CrossFit® Games	133.857 male and female participants	Develop specific benchmarks for different type of workouts	Performance data	Performance benchmarks: Fran male: 250 ± 106 s, Fran female: 331 ± 181 s, Grace male: 180 ± 90 s, Grace female: 213 ± 96 s, Helen male: 9.5 ± 1.9 min, Helen female: 11.1 ± 2.4 min, F50 male: 24.4 ± 5.9 min, F50 female: 27.3 ± 6.9 min, FGB male: 335 ± 65 repetitions, FGB female: 292 ± 62 females)	Physical characterization
Prado Dantas et al. [82]	Brazil	> 1 yr	10 male CrossFit® participants (age: 29.0 ± 6.3 yrs, training experience: NR)	Examine the effects of CrossFit® sections in hemodynamic indicators	Hemodynamic variables	Differences were found immediately after the training sessions and 40 min later in systolic blood pressure Diastolic blood pressure was significantly differences between groups 40 min after the sessions	Physiological characterization
Ouellette et al. [83]	U.S	> 6 months	5 male and 10 female CrossFit® participants (age – male: 30.0 ± 8.0 yrs, female: 32.0 ± 5.0 yrs, training experience: NR)	Determine if upright is appropriate during the recovery process between sets	Work rate, heart rate, respiratory rate, oxygen uptake	Statistical differences were found between passive and active recovery strategies Passive strategies (i.e. seating) ↑ work rate Passive strategies were associated with ↑ heart rate, respiratory rate and oxygen consumption	Physical – recovery

Table 1 (continued)

Study	Country of contact author	Inclusion criteria (CrossFit® practice)	Sample characteristics	Aim	Main methodologies/ variables extracted	Main results	Main topic
de Sousa et al. [84]	Brazil	> 1 yr	13 male CrossFit® participants (age: 26.0 ± 3.0 yrs, training experience: NR)	Compare physical capacities considering two different types of practice (CrossFit® and recreational participants)	Body size, body composition, fixed bar pull-ups (relative strength of upper limbs), 20-m shuttle run, countermovement jump	Comparison between groups did not show differences on body composition, pull-ups and countermovement jump ↑ countermovement jumps in CrossFit® participants ↑ shuttle-run test in CrossFit® participants ↑ relative strength of upper limbs in resistance training participants	Comparison by competitive level
Fernández-Fernández et al. [85]	Spain	NR	10 CrossFit® participants (age: 30.0 ± 4.2 yrs, training experience: 1.0 ± 0.2 yrs)	Examine physiological parameters on different type of WODs (Fran and Cindy)	VO_{2max}, HR, blood lactate, energy expenditure and RPE	Differences on metabolic parameters were found for VO_{2max} and energy expenditure in different training sessions ↑ values of oxygen consumption, %VO_{2max}, energy expenditure were reported Cindy workout	Compare different workouts
Butcher et al. [86]	Canada	> 1 yr	10 male and 4 female CrossFit® participants (age: 32.7 ± 5.7 yrs, training experience: 3.9 ± 2.0 yrs)	Determine the impact of physiological and strength measurements on CrossFit® WODs (Grace, Fran, Cindy)	CrossFit® performance, VO_{2max}, Wingate test	Grace and Fran were related with whole body strength (Grace: r=—0.88, Fran: r = -0.65) and anaerobic threshold (Grace: r=—0.61, Fran: r=—0.53) No significant associations were noted for Cindy	Physical characterization

Table 1 (continued)

Study	Country of contact author	Inclusion criteria (CrossFit® practice)	Sample characteristics	Aim	Main methodologies/ variables extracted	Main results	Main topic
Bellar et al. [10]	U.S	> 1 yr	21 male CrossFit® participants (age: 26.7 ± 4.3 yrs, training experience: NR)	Determine the importance of aerobic and anaerobic capacity on performance	Aerobic capacity, anaerobic power	Experience participants had ↑ performance in as many rounds as possible and performed ↓ time to complete the workout than unexperienced participants Training experience, maximum aerobic capacity, peak power and age were associated with ↑ repetitions in first workout Training experience was the unique significant predictor in the 21–15-9 workout	Physiological characterization

NR Not reported, *HR* Heart rate, *RPE* Rate of perceived exertion, *RPD* Rate of perceived discomfort, VO_{2max} Maximal oxygen uptake, *RER* Respiratory exchange ratio, *RM* Maximal repetition, *CK* Creatine kinase, *PRS* Perceived recovery status

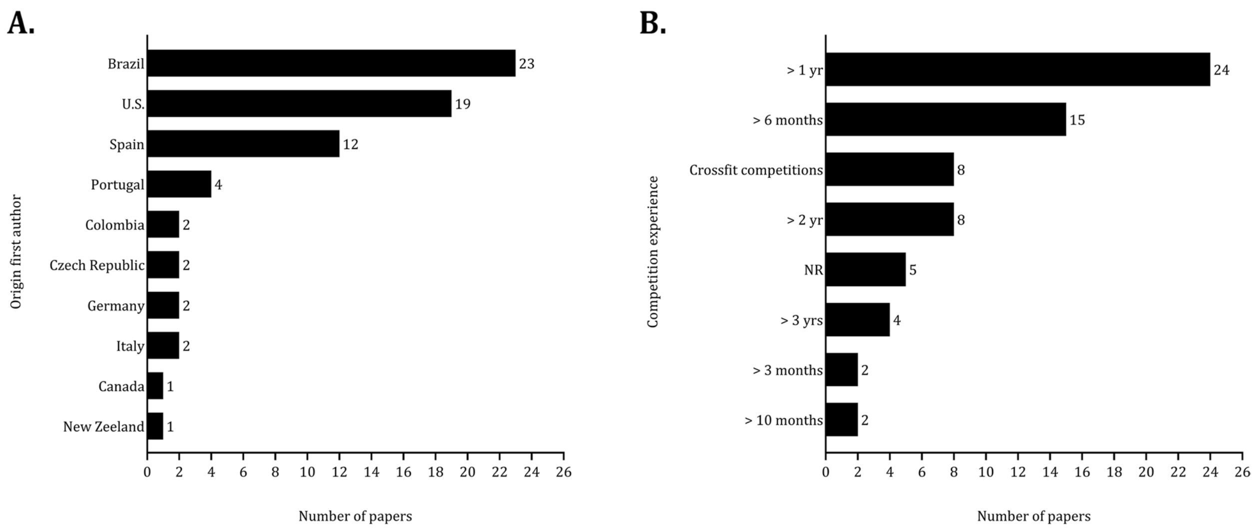


Fig. 2 Frequencies of studies published considering the origin of the first author (**A**) and the athletes' experience (**B**)

for time workout [45]. Figure 3 (panel B) indicates considerable variation between subjects. Mean heart rate differs substantially when the workouts are compared (Fig. 3, panel C). Higher mean heart rate values were observed in response to Fran's (179 ± 8 beats·min^{-1}) and Cindy's (182 ± 7 beats·min^{-1}) workouts. The mean value registered for the Murph workout was 169 ± 6 beats·min^{-1}. Comparing the lactate measured immediately after CrossFit® sessions, the highest mean values were observed following rounds for time workouts. The lowest lactate values were noted following Cindy, Fran, and Murph's workouts (Fig. 3, panel D). The values of the ratings of perceived exertion, considering exclusively the studies that used the Borg scale 1–10, showed that rounds for time tend to be classified as the most physically demanding (Fig. 4). Body composition data indicated that male participants (overall mean considering two studies: 10.5%) presented lower values of fat mass percentage than females (overall mean considering two studies: 16.3%) (Fig. 5).

Recovery was assessed following a number of different CrossFit® workouts, with Fran [20, 46], Karen [43], Fight Gone Bad [10], Cindy [41], and Isabel [21] being the most examined workouts, while other studies classified the workouts as many rounds as possible or rounds for time [68]. Recovery was assessed after each workout using measures of physical performance (i.e., jumping, plank time) or physiological outcomes (i.e., heart rate, lactate, CPK). One study investigated the jumping and plank performance until 24 h after the Fran workout [20]. Physiological parameters were measured immediately-, 10-, 20-, and 30-min post-Fran workout [76]. As shown in Fig. 6, 30 min and 24 h after are not sufficient for the physical and physiological parameters to return to the baseline. The recovery process was also examined following Karen's workout using jumping height and creatine kinase as measures of recovery [43]. Jumping performance was comparable between baseline and 72 h after the Karen workout, whilst creatine kinase was substantially higher 72 h post-Karen workout (baseline: 151.1 ± 68.3; 72-h post-training: 223.0 ± 86.3, Fig. 7). Heart rate and lactate values 30 min after Open 18.4, Fight Gone Bad, and Cindy workouts were also higher than baseline [41, 76]. The same trend was noted in heart rate 5 min after the Isabel workout [21] (Figs. 8, 9, and 10). Although a separate study did not report the differences between the types of workouts, two different types of workouts were used – as many rounds as possible and rounds for time [68]. Physical performance returned to baseline 48 h post-workouts, while the physiological markers were comparable to baseline 72 h after the workout (Figs. 11 and 12).

Table 2 summarizes the studies assessing the chronic effects of CrossFit® participation [67, 69]. Six weeks was not sufficient to improve the physical performance outputs, but 8 weeks of CrossFit® participation resulted in increases in testosterone and decreases in cortisol levels. Using the same participants, only one interventional study assessed the change in physiological response (blood lactate, heart rate, ratings of perceived exertion, and ratings of discomfort) to different types of training (Cindy workout vs. continuous running) [23]. The mean heart rate was comparable in both groups. However, the maximal heart rate, blood lactate, ratings of perceived exertion, and ratings of perceived discomfort were higher during Cindy's workout. Separate investigations

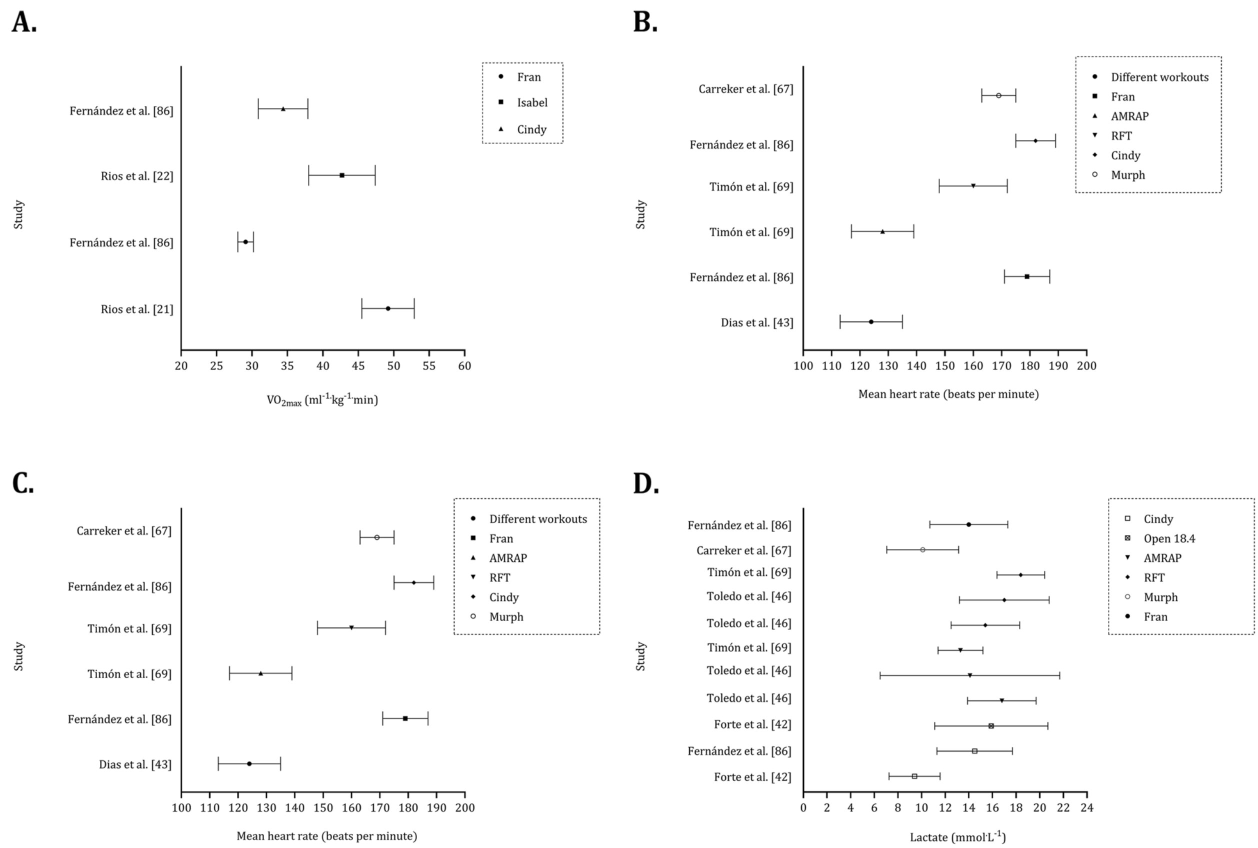


Fig. 3 Physiological indicators reported according to type of CrossFit® challenge

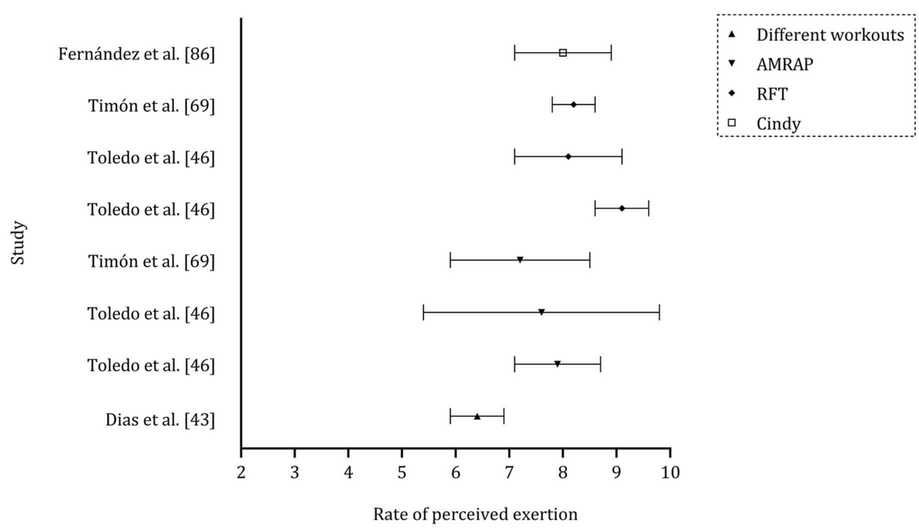


Fig. 4 Rate of perceived exertion considering different types of CrossFit® challenges

compared CrossFit® athletes with other groups, including runners [22], sedentary populations [25], athletes completing cross-training exercise [54], physically active cohorts [25], and resistance training participants [12, 84] in relation to changes in body composition, physiological responses, and physical performance.

Table 3 presents data for body composition and $VO_{2max.}$ CrossFit® participants had lower values of fat

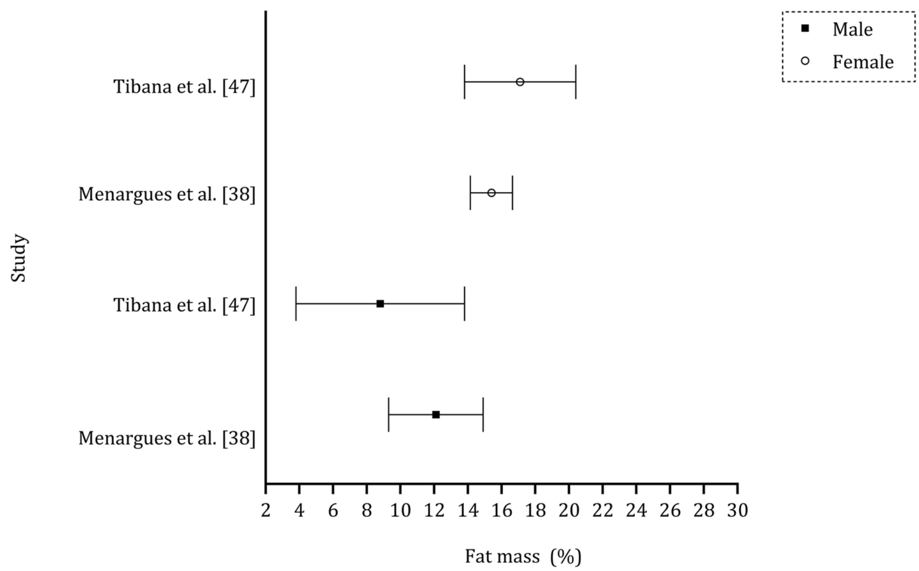


Fig. 5 Mean values of fat mass percentage splitting by sex

mass percentage than sedentary [25], cross-training [54], or physically active individuals [65]. The VO_{2max} of CrossFit® athletes was higher than the sedentary group [25] and lower than the runners [22]. CrossFit® participants also demonstrated superior physical performance (jumping performance, box-jump, pull-ups, push-ups, burpees, maximum speed) than cross-training [54] and resistance training participants [84].

Interventional [27, 34, 62] and observational studies [10, 28, 60] examined variation by competitive level. Two studies compared the mean and maximal heart rate in experienced and less experienced participants after implementing different training sessions [27] and Cindy workouts [62]. Mean values were equivalent between groups. Cognition variables were measured in 32 Crosss-Fit® athletes classified as elite, advanced, and beginner participants after Fran workouts [34]. All groups differed significantly between pre- and post-Fran workout. Additionally, two observational studies showed that CrossFit® participants of elite or advanced levels had lower fat mass values than those at the middle or recreational level [28, 60]. Strength variables were also affected by the competitive level of participants, with more experienced athletes showing higher values in the maximal repetition test [60], isometric mid-thigh pull assessment [28], rate of force development [28], and power [10].

Meta-correlation

Challenges focused on completing as many rounds as possible

Studies that used specific protocols of CrossFit® (back squat, front squat, snatch, clean and jerk) found a positive and moderate relationship between challenges focused on completing as many rounds as possible ($r=0.33$; 95% CI:—0.09 to 0.65), which means that participants who lift more weight on strength protocols complete more rounds on the workouts. The magnitude of correlation increased when the specific protocols were expressed per kilogram of body mass ($r=0.38$; 95% CI: 0.03 to 0.65; $p=0.03$) (Figs. 13 and 14). In contrast, non-specific protocols were not associated with performance in as many rounds as possible workout. The values of heterogeneity were high and moderate for specific ($I^2=77.1\%$) and specific protocols relativize for body mass ($I^2=67\%$), respectively.

Challenges focused on completing the workout fasting as possible

When the workouts focused on completing the challenge as fast as possible, time and specific CrossFit® protocols were not associated, as shown in Fig. 15. The overall correlation coefficient was positive ($r=-0.18$; 95% CI: -0.36 to 0.01; $p=0.07$), demonstrating that athletes who were faster on challenge performed less strength on specific protocols. Similar results were obtained for non-specific CrossFit® protocols.

Specific workouts

Studies with correlation data between protocols and performance were available for the following workouts: Cindy, Fran, Donkey Kong, Grace, Murph, and Nancy. For Murph and Nancy workouts, data was limited, and for this reason, a meta-correlation was not conducted.

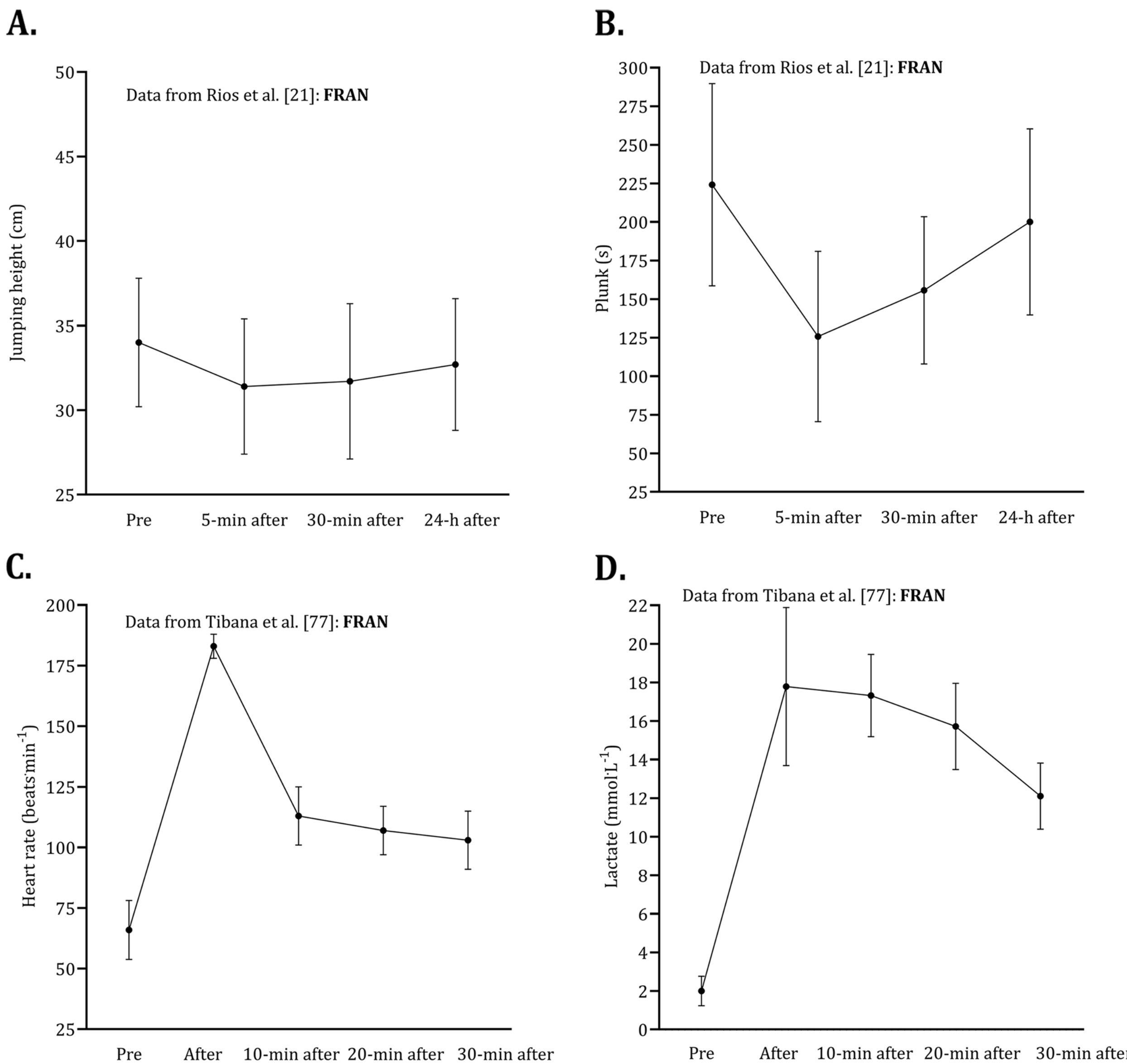


Fig. 6 Physical and physiological variation before and after Fran challenge

For the Cindy workout (which comprises completing as many rounds as possible in 20 min of five pull-ups, ten push-ups, and fifteen air squats), only one study (Butcher et al., 2015) tested the association between the number of rounds complete and non-specific (Wingate test and VO_{2max}) and specific protocols (CrossFit®). As shown in Supplementary Material 1, the combination of different protocols resulted in a non-significant association with rounds performed on Cindy workout ($r = 0.14$; 95% CI: -0.15 to 0.41; $p = 0.33$).

The Fran challenge involves completing as fast as possible three rounds of 21, 15, and 9 repetitions of two exercises: thrusters and pull-ups. The meta-correlation of sub-groups (specific and non-specific) noted significant magnitudes of associations between types of protocol and performance (Fig. 16). A negative correlation coefficient indicated that more time to complete the challenge was associated with better performance in protocols. A small and non-significant association between Fran performance and non-specific protocols ($r = 0.24$, $p = 0.19$) was found. In opposition, specific protocols were moderately associated with performance in the Fran challenge ($r = -0.44$; 95% CI: 0.22 to 0.54; $p < 0.05$). The value of heterogeneity was high ($I^2 = 75\%$).

On the Donkey Kong challenge, CrossFit® participants should complete as fast as possible three rounds

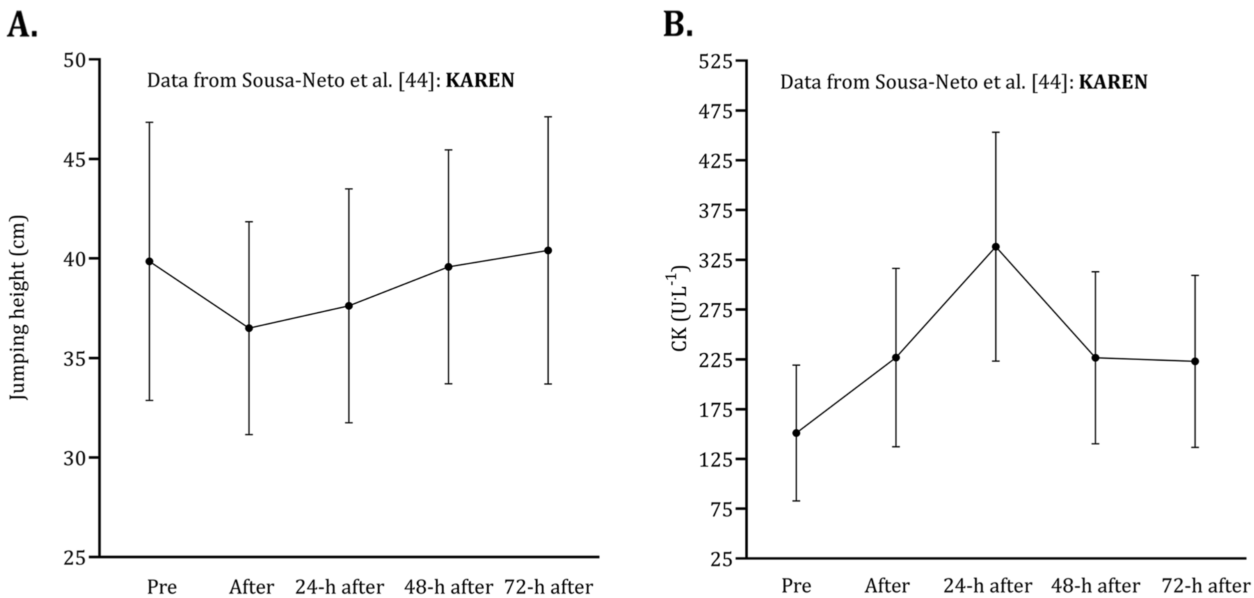


Fig. 7 Physical and physiological variation before and after Karen challenge

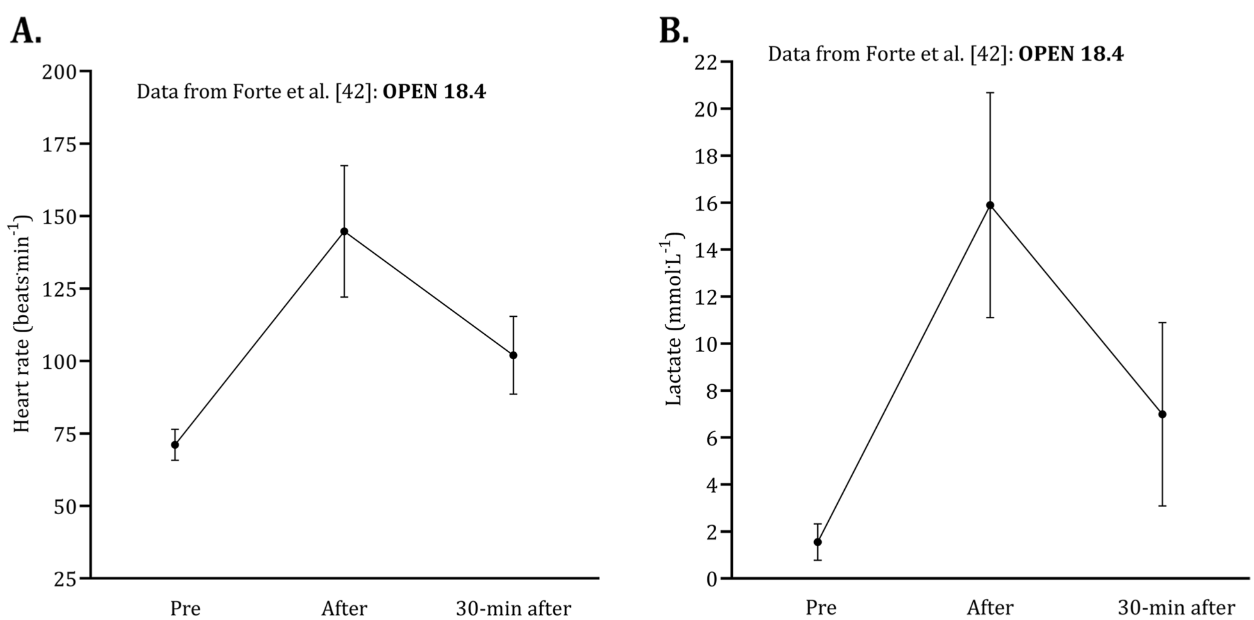


Fig. 8 Physical and physiological variation before and after Open 18.4 challenge

of 21, 15, and 9 repetitions of burpees, kettlebell swings, and box jumps. After each exercise, participants need to perform six lunges. A negative correlation coefficient indicated that less time to complete the challenge was associated with a better performance in Donkey Kong challenge. Only one study examined the relationship between different protocols and performance in this challenge (Gomez-Landero et al., 2020). For non-specific protocols, the study included four different protocols: sit-ups, hand dynamometers, $VO2_{max}$ estimated from a shuttle-run test, and peak power derived from countermovement jumps. Specific protocols used were pull-ups, bench presses, and squats. Non-specific protocols were significantly related with performance, while the overall magnitude of correlation in specific protocols was small and non-significant ($r = -0.26$; 95% CI: -0.06 to 0.53; $p = 0.11$) (Supplementary Material 2).

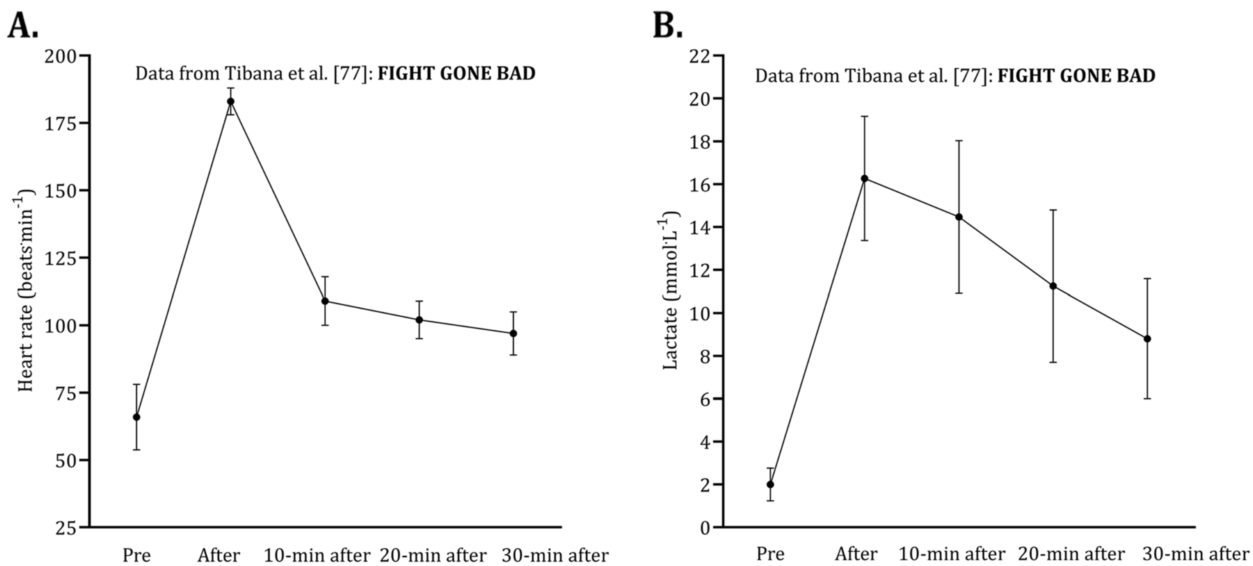


Fig. 9 Physiological variation before and after Fight Gone Bad challenge

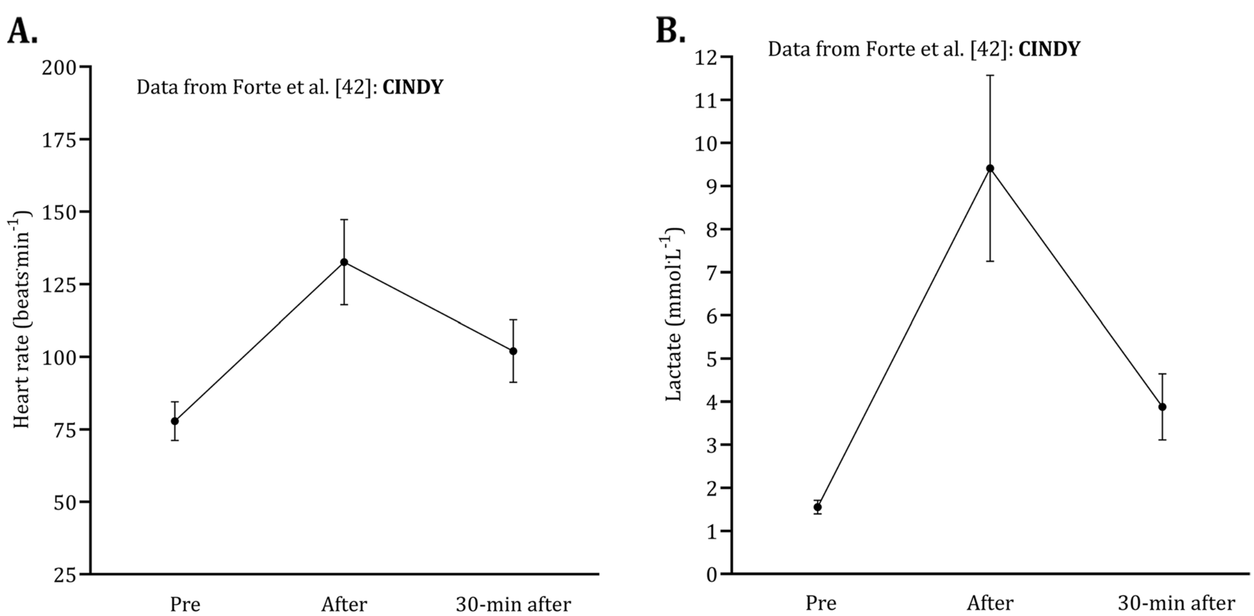


Fig. 10 Physiological variation before and after Cindy challenge

The Grace challenge consists of performing 30 repetitions of clean and jerk as fast as possible, which means a negative correlation represents less time to complete the workout. Non-specific protocols were not associated with performance on Grace performance. On the other hand, total strength, strict press, deadlift, and back squat exercises were related to Grace performance ($r = 0.478$; 95% CI: 0.177 to 0.697; $p = 0.003$). The heterogeneity across studies was moderate ($I^2 = 62\%$) (Fig. 17).

Discussion

The aim of this scoping review was to characterize the physical demands and physiological responses to CrossFit®. The findings and potential gaps in the scientific literature that emerged from the current review were as follows: (1) CrossFit® studies have mainly been undertaken in North and South America; (2) the definition of a CrossFit® athlete is not clear in the literature with different cut-off values being used to include participants in the studies; (3) a limited number of studies focused on

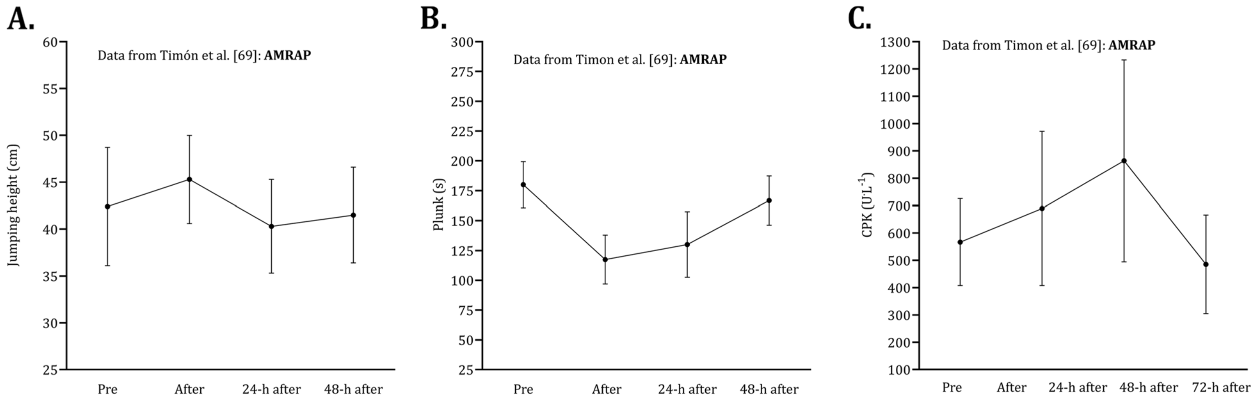


Fig. 11 Physical and physiological variation before and after as many rounds as possible workouts

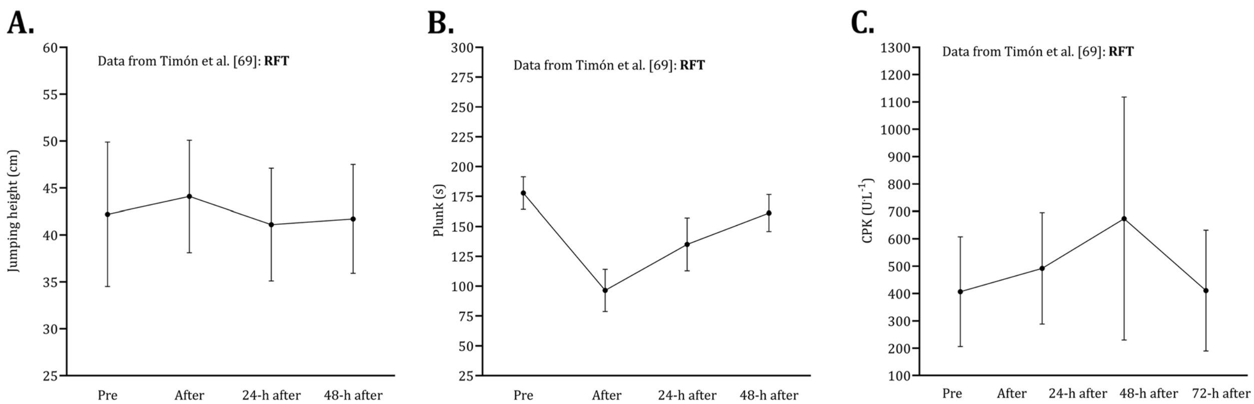


Fig. 12 Physical and physiological variation before and after rounds for time workouts

Table 2 Studies[a] that described the chronic effects of CrossFit® participation

Study	Time of practice	Output	Result
Poderoso et al. [69]	2 months	Testosterone	↑
	4 months		↑
	6 months		↑
	2 months	Cortisol	↓
	4 months		↓
	6 months		↓
Cardeñosa et al. [67]	6 weeks	Heart rate[b]	↔
		Maximal power	↓
		VO_{2max}	↔
		Sum of six skinfolds	↑

[a] Data from da Silveira Castanheira et al. [18] was not provided. [b]heart rate was derived from an incremental test; ↔ = no difference, ↑ = increased, ↓ = reduced

characterizing the physiological and physical parameters of different workouts; (4) body composition data suggest that males have less fat mass percentage than females; (5) recovery strategies for CrossFit® should be investigated in order to optimize weekly performance and physiological markers; (6) the literature relation to the chronic effects of CrossFit® is scarce, although the study that did exist in this area demonstrated that six weeks was not sufficient to promote significant changes in physical and physiological parameters, while eight weeks led to increases in testosterone and decrements in cortisol; (7) in comparison to other exercise modalities (i.e., resistance training, endurance), CrossFit® elicits greater benefits to body composition and maximal oxygen uptake; (8) it was not possible to determine a unique predictor of CrossFit® performance; (9) movements specific to CrossFit® seem to be more related to CrossFit® performance than non-specific protocols.

An early study compared three groups across ten weeks, with participants either undertaking aerobic training ($n = 8$), resistance training ($n = 8$), or concurrent training ($n = 7$) [88]. Concurrent training involves the inclusion of resistance training (to gain strength, hypertrophy, and power) combined with aerobic exercise (to enhance endurance) [89]. A reduction in lower body strength was found in the concurrent training group

Table 3 Observational studies comparing Crossfit® with other activities or control group

Variable	Study	Crossfit® vs. comparator	Crossfit®	Comparator
			Mean ± sd	Mean ± sd
Fat mass, %				
	Carvalho et al. [22]	vs. runners	19.0 ± 6.3	18.2 ± 6.3
	Pearson et al. [25]	vs. sedentary	18.6 ± 3.8	30.3 ± 8.4
	Fernando et al. [54]	vs. crosstraining	16.5 ± 27.5	18.0 ± 3.0
	Cavedon et al. [65]	vs. physical active	12.9 ± 2.7	18.9 ± 3.3
	Barbieri et al. [74]	vs. resistance training	11.8 ± 4.9	14.1 ± 5.3
	de Sousa et al. [84]	vs. resistance training	13.6 ± 4.6	11.9 ± 4.1
Lean mass, kg				
	Pearson et al. [25]	vs. sedentary	64.6 ± 11.7	50.7 ± 6.3
	Cavedon et al. [65]	vs. physical active	65.0 ± 6.4	64.8 ± 6.2
	Barbieri et al. [74]	vs. resistance training	59.8 ± 10.7	49.6 ± 8.1
VO_{2max}, $ml{\cdot}kg^{-1}{\cdot}min^{-1}$				
	Carvalho et al. [22]	vs. runners	41.8 ± 5.4	50.0 ± 10.8
	Pearson et al. [25]	vs. sedentary	43.3 ± 3.9	31.1 ± 3.8
	Barbieri et al. [74]	vs. resistance training	42.5 ± 5.3	44.4 ± 5.5
	de Sousa et al. [84]	vs. resistance training	52.5 ± 5.6	46.0 ± 5.8

sd Standard deviation

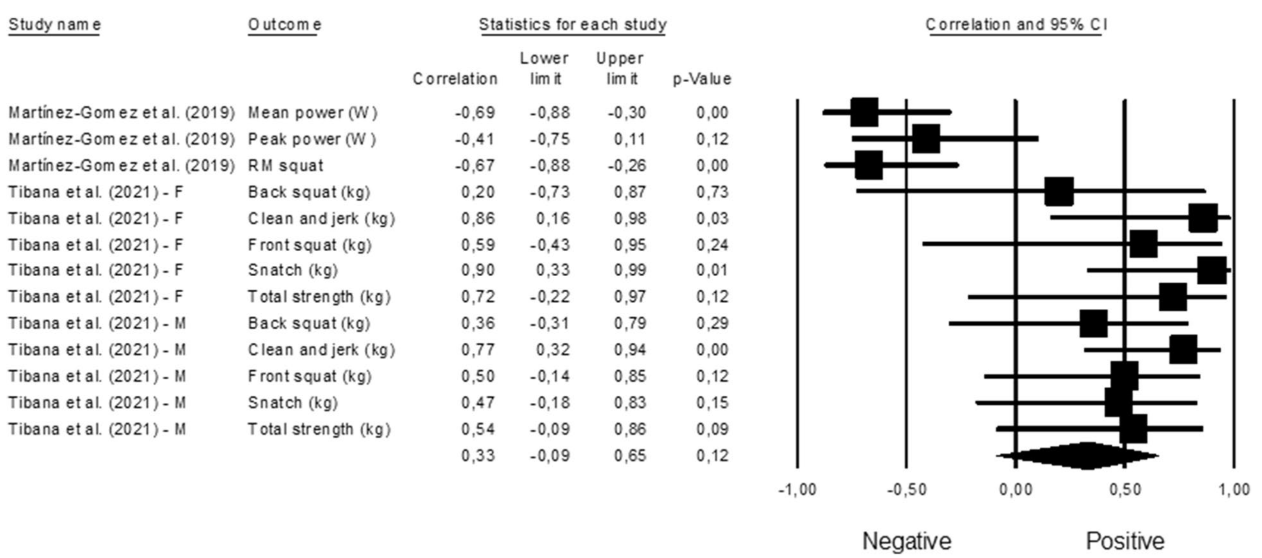


Fig. 13 Meta-correlation between specific protocols and CrossFit® workouts classified as many rounds as possible. F (female); M (male). Note: positive indicates positive performance

compared to resistance exercise. It was hypothesized that aerobic training negatively impacted the resistance training adaptations, termed the "interference effect" [66]. In a meta-analysis that combined 21 studies, resistance training promoted higher gains in hypertrophy, strength, and power than concurrent protocols [90]. This study also concluded that the type and volume of endurance training impact the "interference effects" of resistance training [90]. While in the meta-analysis, the details of studies were not presented, the participants of the concurrent training group included in the original research about the "interference effect" completed the resistance training and endurance protocol separated by two hours [88]. The training sessions of CrossFit® incorporated both endurance and resistance exercises within the same session, which suggests the "interference effect" cannot be generalized for CrossFit® participants. Nevertheless, more recent studies about the short-term effects of concurrent

Study name	Outcome	Correlation	Lower limit	Upper limit	p-Value
Martínez-Gomez et al. (2019)	Mean power (W/kg)	-0,51	-0,80	-0,02	0,04
Martínez-Gomez et al. (2019)	Peak power (W/kg)	-0,14	-0,59	0,38	0,61
Martínez-Gomez et al. (2019)	RM squat (per kg)	-0,50	-0,80	-0,01	0,05
Tibana et al. (2021) - F	Back squat (per kg)	0,12	-0,77	0,85	0,83
Tibana et al. (2021) - F	Clean and jerk (per kg)	0,89	0,28	0,99	0,01
Tibana et al. (2021) - F	Front squat (per kg)	0,52	-0,50	0,94	0,32
Tibana et al. (2021) - F	Snatch (per kg)	0,92	0,43	0,99	0,01
Tibana et al. (2021) - F	Total strength (per kg)	0,68	-0,29	0,96	0,15
Tibana et al. (2021) - M	Back squat (per kg)	0,39	-0,27	0,80	0,24
Tibana et al. (2021) - M	Clean and jerk (per kg)	0,75	0,27	0,93	0,01
Tibana et al. (2021) - M	Front squat (per kg)	0,51	-0,13	0,85	0,11
Tibana et al. (2021) - M	Snatch (per kg)	0,48	-0,17	0,84	0,14
Tibana et al. (2021) - M	Total strength (per kg)	0,54	-0,09	0,86	0,09
		0,38	0,03	0,65	0,03

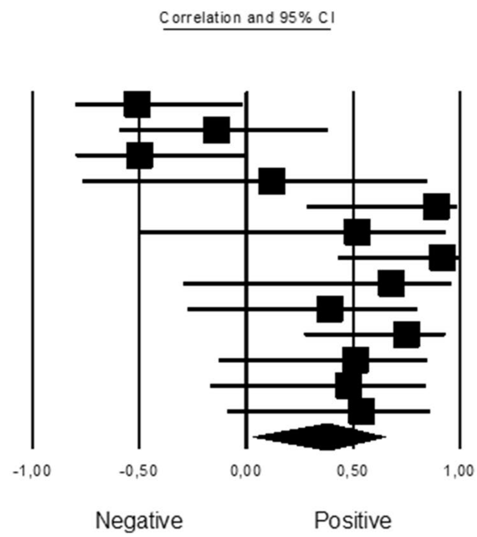


Fig. 14 Meta-correlation between specific protocols normalized for body weight and CrossFit® workouts classified as many rounds as possible. F (female); M (male). Note: positive indicates positive performance

training on muscle hypertrophy showed contradictory findings questioning the "interference effect" theory [87, 91, 92]. A parallel study compared two different conditions (resistance training in isolation vs. concurrent training [i.e., combining cycling activities with resistance training]) across a 7-week program on muscle size and specific indicators of protein synthesis and degradation [91]. Muscle fiber area increased significantly in the concurrent training group, whilst negligible changes were noted in the resistance training group. The levels of the mechanistic target of rapamycin (i.e., an indicator of muscle mass development) were also raised in concurrent training, highlighting the anabolic effects when endurance and resistance activities were combined [91]. In the present review, CrossFit® participants had higher mean values of lean mass in comparison to physically active [65] and resistance training [74] participants, suggesting the combination of resistance training and endurance exercise within the same training session could potentiate the development of muscle mass. Participation in CrossFit® sessions over 8 weeks also demonstrated increases in testosterone and decreases in cortisol.

The main findings pertaining to concurrent training are modulated by the training status of participants and the methodologies used to assess changes in muscle strength and hypertrophy [5]. Three to nine months were proposed to classify an athlete as "trained" for a resistance and endurance athlete [5]. Although most of the studies included in the present review attained these criteria, the literature focused exclusively on the best athletes was scarce. Strength, power, and body composition distinguished elite athletes from lower competitive levels [10, 28, 60]. Moreover, considering the CrossFit® Open allows everyone to participate, significant variability in physical performance is expected. Future studies should focus on examining participants considering the different phases of CrossFit® competition: CrossFit® Open, quarterfinals, semi-finals, and CrossFit® Games. It might then be possible to discriminate participants according to training status and not focus exclusively on training time. Specificity was another concept claimed to define training status, particularly task-specific activities related to maximal strength. Hypertrophy is not exercise-dependent [5, 93], while changes in strength are exercise- and intensity-dependent (i.e., specific).

The relationship between CrossFit® performance and different protocols seems specific, with movements often carried out during CrossFit® sessions (e.g., back squat, front, deadlift, clean, clean and jerk) being more related to performance. In contrast, non-specific protocols were rarely associated with CrossFit® performance. For those who train CrossFit® athletes, the application of specific protocols has more relevance. Whereas, on the other hand, the results of the current meta-correlation also showed that it is difficult to generalize a particular test for all types of workouts. This is in line with a systematic review that described back squat and total body strength as the main variables to explain performance. However, variation in the results across the 21 studies included indicates that a consensus about predictors could not be generalized [9]. Considering the variability of CrossFit® in terms of exercises and intensity, this point is not surprising. The variability of physical and physiological indicators to explain the performance in CrossFit® workouts

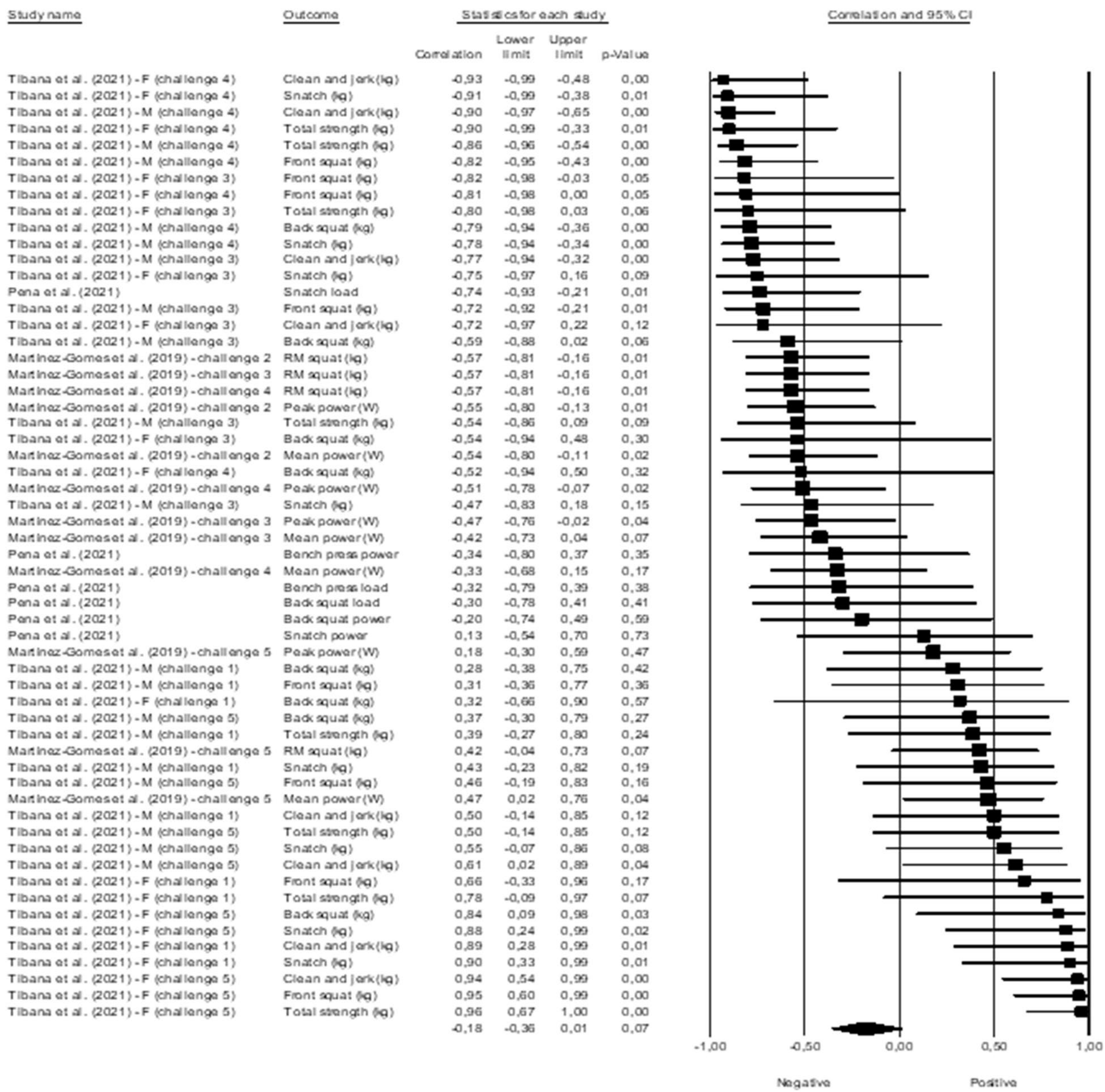


Fig. 15 Fig. 14. Meta-correlation between specific protocols and CrossFit® workouts classified as time to complete. F (female); M (male). Note: positive indicates positive performance

was noted, which indicates that the predictors of a typical endurance workout should not be generalized for a resistance workout [21, 28, 42, 66, 79]. In order to support coaches in the monitoring, quantification, and regulation of training load, future studies need to investigate the physical and physiological characteristics of other specific workouts.

A considerable number of studies used physical and physiological outputs to examine recovery after a CrossFit® workout [20, 41, 43, 68, 88]. In general, 48–72 h were insufficient to obtain the baseline values of physical and physiological markers, and these studies only focused on a specific challenge. A typical CrossFit® session includes other components rather than the workout of the day (e.g., strength, mobility, stability, skill). In order to prevent fatigue and optimize performance, research is needed on which recovery strategies for CrossFit® athletes are needed [6, 14].

The inclusion of papers solely written in English, Portuguese, and Spanish is a limitation of the current

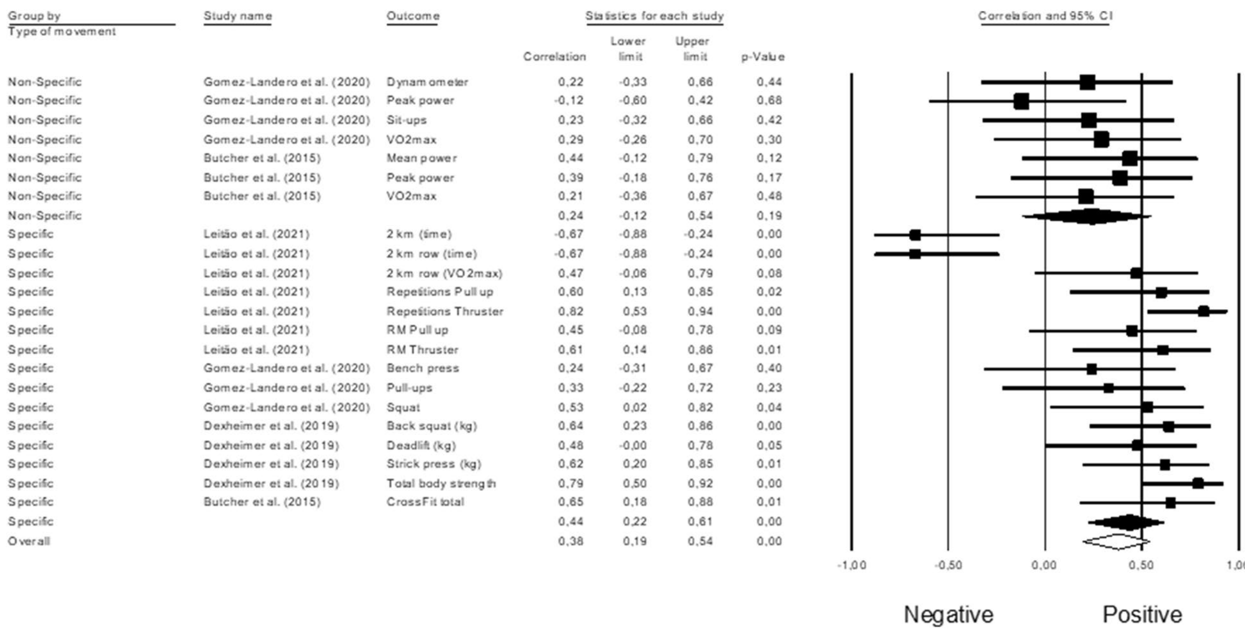


Fig. 16 Meta-correlation between specific, non-specific protocols and Fran performance. Note: positive indicates positive performance

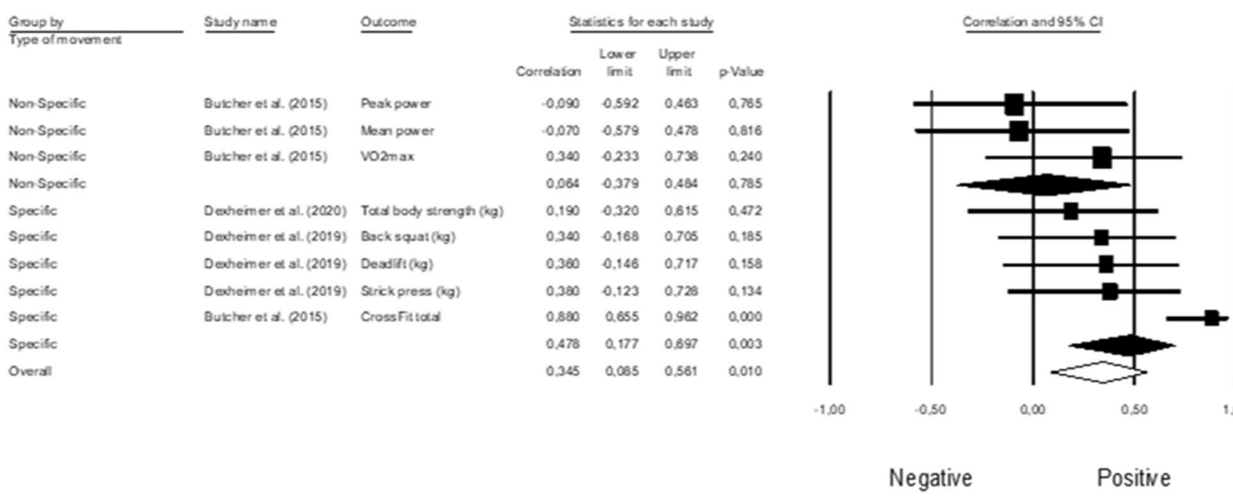


Fig. 17 Meta-correlation between specific, non-specific protocols and Grace performance. Note: positive indicates positive performance

review. Studies about injuries or psychological variables were not considered since these topics were previously discussed in the literature [13, 94]. The non-uniform criteria relating to training experience required to qualify as a CrossFit® athlete is the major limitation of the eligible studies. Consequently, the participants' level must be discriminated in the sampling description. In most of the studies, a specific workout's physical or physiological description did not always consider the entire training session. Consequently, future studies should investigate training sessions' physical and physiological aspects individually or combined in microcycles or mesocycles.

Conclusion

CrossFit® seems to align with the recent benefits described in concurrent training, although they are modulated by training status and specificity of exercise. The definition of CrossFit® athlete needs to be considered in future studies since everyone can perform CrossFit Open®. In this competition, significant variability in performance and participants' characteristics are observed, influencing the interpretation of results. The correct manipulation of the training load is an additional issue for coaches in order to optimize performance and prevent fatigue. Coaches should be aware that the design and implementation of CrossFit® programs require specific information about the metabolic demands of each workout. Consequently, they should use training tools to control the volume and intensity of training to manage the training load. In order to interpret performance, protocols with specific CrossFit® movements should be routinely applied, even though it was challenging to obtain a test for all workouts. Therefore, further research needs to be conducted to characterize workouts that induce distinct physical and physiological responses.

Supplementary Information

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Supplementary Material 1.

Supplementary Material 2.

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Authors' contributions
DS, DVM, ERG, HS conceptualized the manuscript. DS, DVM, ERG, HS wrote the protocol and methodology. DVM, AR, CA, DSB, NS used and managed the software. DVM, ERG, AS, AF, HS organized the data. DVM, AR, CA, NS, AS writing the original draft. DS, DVM, CM, AF, ERG, HS wrote and reviewed the manuscript.

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