To Prepare Athletes for 'the Unknown and the Unknowable': Characterization of Major Challenges in CrossFit® Science

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Für Stephan

„Hard Work Pays Off“

- Mat Fraser, 2022
(Five-time 'Fittest Man on Earth®')

Abstract

The new training concept CrossFit® is supposed to build comprehensive fitness and is already applied by several professionals that depend on multisided, functional physical skills, such as police, firefighters, and military units. Also, as a leisure sport, the CrossFit® program quickly developed into a fast-growing and successful brand with approximately 15,000 affiliated training centers worldwide. Thereby, the basic principles are still poorly understood. The training routine involves constantly varied functional movements performed at high-intensity and includes exercises from the main elements of gymnastics (e.g., pull-ups, push-ups, and burpees), weightlifting (e.g., powerlifting, and Olympic weightlifting), and cardiovascular activities (e.g., running, rowing, and jumping), usually referred to as 'Workout of the Day'. Motivated by the intense community character of CrossFit® training, individuals, regardless of whether they are members of special forces, professional athletes, patients with chronic illnesses, disabled, overweight, or untrained people, gladly face the daily workouts and perform them together in the same training sessions due to the scalability of exercises. Thus, the concept of CrossFit® training works effectively, although it has not yet been scientifically evaluated or understood in detail why or how. Characteristic differences from other sports, such as the constant variation of the training stimuli, the unpredictability of the competitions, and psycho-social aspects of the community, require a detailed scientific analysis of CrossFit® in order to provide practical recommendations for athletes and coaches. For this reason, a number of research questions were considered in parallel and summarized in this thesis with the overarching aim of providing a detailed insight into the nature of CrossFit®. In this context, the focus of this thesis is on (a) investigating the acute, short-term physiological and cardiovascular responses of CrossFit® training, (b) determining a CrossFit® performance profile and assessing the predictors of competitive performance, and (c) examining the impact of the consequences of the COVID-19 pandemic on training behavior of CrossFit® athletes and describing the way the athletes dealt with the new situation. Within this thesis, two intervention studies and two questionnaire surveys were conceived to address these issues. In detail, the experimental analysis of physiological parameters (rating of perceived exertion, blood lactate, and heart rate [HR] values) of an ultra-short, intense CrossFit® workout was intended to provide whether short CrossFit® workouts (< 2 min) lead to an increase in blood lactate concentration after the completion of the workout and whether the rating of perceived exertion is related to the increase in lactate concentration. Within this pilot study, for the first time, a time-delayed increase in blood lactate values was observed, as is known from short runs, although not from CrossFit® workouts. In a further study, cardiovascular demands were analyzed in four different training sessions at a local training center to assess physiological responses not on isolated workouts separately, even during 1-h sessions. In this regard, the observational study of athletes of different experience levels provides an analysis of practical CrossFit® training settings. The data suggest that the previous assumption that CrossFit® training is performed predominantly in the HR range above 90% of HR_{max} is misunderstood. Rather, the results suggest that the CrossFit® training provides a progressive cardiovascular load increase during 1-h training sessions and that beginner and experienced athletes, regardless of individual CrossFit® experience, push themselves to the limit without significant differences in cardiovascular response to the training stimulus. Given the lack of valid data in the scientific literature on performance parameters of CrossFit® athletes and the non-existing knowledge of regional differences, another research project was conceived to target this issue. For this reason, data from American and German athletes were collected by a questionnaire survey to determine a CrossFit® Benchmark performance profile. The results demonstrate no overall performance difference between the nations and suggest an important role of the back squat performance in the assessment of the physical fitness of CrossFit® athletes. Furthermore, the ongoing course of the COVID-19 pandemic also poses unprecedented challenges. For this reason, the following research investigated the use of digital sports offers, training habits, body weight changes, and purchase of sports equipment during the first SARS-CoV-2 lockdown in Germany *via* an online questionnaire. As a result, the data show that CrossFit® athletes purchased new equipment for a home gym and the use of digital sports increased significantly across all age groups. Despite the massive restrictions, the athletes were able to continue their training, and thereby, a subgroup reported a significant reduction in body weight, which may lead to an improvement in body composition and health-related aspects. In summary, the studies provide new insights into the physiological parameters of CrossFit® training, which constitute the foundation for prospective, controlled long-term trials. Based on the results, future research may investigate the performance- and health-promoting effects of CrossFit® in more detail. Nevertheless, this thesis contributes to major challenges in CrossFit® science by improving the comprehension of physiological demands, performance assessment, and training behavior of CrossFit® athletes, even during challenging times.

Keywords. Blood lactate, Body weight, CrossFit®, COVID-19, Digital sport, Exercise intensity, Fitness, Functional fitness training, Heart rate, High-intensity functional training, Rating of perceived exertion, Performance profile, Physiological response, Physical activity, Public health, Sport science, Training behavior

Kurzfassung

Das neue Trainingskonzept CrossFit® zielt auf die Entwicklung einer sportartübergreifenden Fitness ab und wird daher bereits von verschiedenen Berufsgruppen, die vielseitige und funktionale körperliche Fähigkeiten erfordern, wie z.B. Polizei-, Feuerwehr- und militärische Einheiten, als Trainingsmethode eingesetzt. Auch als Freizeitsport hat sich CrossFit® innerhalb kürzester Zeit zu einer erfolgreichen Marke mit weltweit ca. 15.000 angeschlossen Trainingseinrichtungen entwickelt. Das Fitnessprogramm beinhaltet ständig variierende, funktionale Bewegungen, die mit hoher Intensität ausgeführt werden und umfasst Übungen aus den Hauptelementen des Turnens (z. B. Klimmzüge, Liegestütze und Burpees), des Gewichthebens (z.B. Kraftdreikampf und olympisches Gewichtheben) und des Herz-Kreislauf-Trainings (z. B. Laufen, Rudern und Seilspringen), die in der Regel als *'Workout Of the Day'* bezeichnet werden. Motiviert durch den starken Gemeinschaftscharakter stellen sich die Sportler, ob Angehörige von Spezialeinheiten, Profisportler, Patienten mit chronischen Krankheiten, bewegungseingeschränkte, übergewichtige oder untrainierte Personen, gerne den täglich wechselnden Herausforderungen und können dank der hohen Skalierbarkeit der Übungen gemeinsam in einer Trainingseinheit trainieren. Das Konzept des CrossFit®-Trainings funktioniert somit effektiv, auch wenn noch nicht im Detail wissenschaftlich evaluiert oder verstanden wurde, warum und wie. Charakteristische Unterschiede zu anderen Sportarten, wie ständig wechselnde Belastungsparameter, unvorhersehbare Wettkampfaufgaben und psychosoziale Aspekte erfordern eine detaillierte wissenschaftliche Untersuchung des CrossFit®-Konzepts, um praktische Empfehlungen für Sportler und Trainer zu ermöglichen. Aus diesem Grund wurden in dieser Arbeit mehrere Forschungsfragen parallel bearbeitet und mit dem übergeordneten Ziel zusammengefasst, einen detaillierten Einblick in das Wesen von CrossFit® zu ermöglichen. Dabei lagen die Schwerpunkte auf (a) der Untersuchung der akuten, physiologischen und kardiovaskulären Reaktionen des CrossFit®-Trainings, (b) der Bestimmung eines CrossFit®-Leistungsprofils und der Bewertung von Prädiktoren für die Wettkampfleistung und (c) der Untersuchung der Auswirkungen der COVID-19-Pandemie auf das Trainingsverhalten von CrossFit®-Athleten. Im Rahmen dieser Arbeit wurden zwei Interventionsstudien und zwei Fragebogenerhebungen konzipiert, um spezifische Forschungslücken zu schließen. Im Einzelnen sollte die experimentelle Analyse physiologischer Parameter (Bewertung der wahrgenommenen Anstrengung, Blutlaktat-, und Herzfrequenzwerte) eines extrem kurzen und intensiven CrossFit®-Workouts Auskunft darüber geben, ob ein derartiges CrossFit®-Workout (< 2 min) zu einem Anstieg der

Blutlaktatkonzentration nach Abschluss der Belastungsphase führt und ob die Bewertung der wahrgenommenen Anstrengung mit dem Anstieg der Laktatkonzentration zusammenhängt. Dabei konnte erstmalig ein zeitverzögerter Anstieg der Blutlaktatwerte beobachtet werden, wie er von Sprints bekannt ist, nicht aber von CrossFit®-Workouts. In einer weiteren Studie wurden die kardiovaskulären Anforderungen in vier verschiedenen Trainingseinheiten in einer lokalen Trainingseinrichtung analysiert, um die physiologischen Reaktionen nicht nur bei isolierten Workouts, sondern auch im Verlauf von 1-stündigen Einheiten zu erfassen. Dabei verhalf die Beobachtungsstudie zu einem besseren Verständnis der praktischen Trainingsbedingungen. Die gemessenen Daten deuten darauf hin, dass die bisherige Annahme, CrossFit®-Training werde überwiegend im Bereich über 90% der maximalen Herzfrequenz durchgeführt, falsch dargestellt wird. Vielmehr legen die Ergebnisse nahe, dass während 1-stündigen Trainingseinheiten eine progressive kardiovaskuläre Belastungssteigerung stattfindet und dass Anfänger und erfahrene CrossFit®-Sportler, unabhängig von der individuellen Trainingserfahrung, in derselben Trainingseinheit bis zur Belastungsgrenze trainieren können, und zwar ohne signifikante Unterschiede in der kardiovaskulären Reaktion auf den Trainingsreiz. Da es in der wissenschaftlichen Literatur an validen Daten zur Leistungsfähigkeit von CrossFit®-Sportlern mangelt und nicht bekannt ist, ob es regionale Unterschiede gibt, sollte ein weiteres Forschungsprojekt diese Problematik aufgreifen. Dazu wurden Daten von amerikanischen und deutschen Sportlern *via* Fragebogen erhoben, um ein breites CrossFit®-Leistungsprofil zu ermitteln. Die Ergebnisse zeigen keinen generellen Leistungsunterschied zwischen den Nationen und deuten auf eine wichtige Rolle der *Back squat*-Leistung bei der Beurteilung der körperlichen Fitness der Sportler hin. Darüber hinaus stellt der anhaltende Verlauf der COVID-19-Pandemie auch CrossFit®-Sportler vor noch nie dagewesene Herausforderungen. Aus aktuellem Anlass wurde daher die Nutzung von digitalen Sportangeboten, Trainingsgewohnheiten, Gewichtsveränderungen und das Kaufverhalten von Sportequipment während des ersten Lockdowns der COVID-19 Pandemie in Deutschland über eine Online-Umfrage untersucht. Die Ergebnisse zeigen, dass sich die Sportler mit neuem Equipment ausstatteten und die Nutzung von digitalen Sportangeboten deutlich zunahm. Trotz der massiven Einschränkungen konnten die CrossFit®-Sportler ihr Training fortsetzen. Dabei berichtete eine Teilgruppe eine signifikante Reduktion des Körpergewichts, wodurch sich potenziell positive Auswirkungen auf die Gesundheit ergeben. Zusammenfassend liefern die Studien somit neue Erkenntnisse über die physiologischen Parameter des CrossFit®-Trainings, die eine Grundlage für prospektive, kontrollierte Langzeitstudien bilden. Auf der Grundlage der Ergebnisse sollten zukünftige

Forschungsarbeiten die leistungs- und gesundheitsfördernden Effekte des CrossFit®-Trainings, einschließlich der entsprechenden Online-Angebote, weiter untersuchen. Folglich leistet diese Arbeit einen Beitrag zu großen Herausforderungen in der CrossFit®-Wissenschaft, indem sie ein besseres Verständnis der physiologischen Anforderungen, der Leistungsbeurteilung und des Trainingsverhaltens von CrossFit®-Athleten, auch in schwierigen Zeiten, ermöglicht.

Schlagwörter: Belastungsintensität**,** CrossFit®, COVID-19 Pandemie, Digitaler Sport, Fitness, Funktionales Fitness Training, Herzfrequenz, *High-intensity functional training*, Körpergewicht, Körperliche Aktivität, Laktat, Leistungsprofil, Lockdown, Sportbiologie, Sportphysiologie, Trainingsverhalten, *Public health*

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List of Abbreviations

1-RM	1-Repetition maximum
A-Part	Skill or power training part of a 1-h training session
ACSM	American College of Sports Medicine
AMRAP	As many repetitions or rounds as possible
bpm	beats per minute
BTWB	Beyond the Whiteboard
B-Part	High-intensity training part of a 1-h training session
BDNF	Brain-derived neurotrophic factor
BMI	Body mass index
CF5	CrossFit® athletes who lost 5 kg body mass
CFA	CrossFit® athletes
CI	Confidence interval
CMJ	Countermovement jump
CPK	Creatine-phosphokinase
EMOM	Every minute on the minute
FT	For time
FFT	Functional fitness training
G	Gymnastics
GH	Growth hormone
HIFT	High-intensity functional training
HIIT	High-intensity interval training
HIMT	High-intensity multimodal training
HR	Heart rate
HR_{max}	Maximal heart rate
IGF-1	Insulin-like growth factor 1
IL-6	Interleukin-6

IL-10	Interleukin-10
KMO	Kaiser–Meyer–Olkin
LAC	Lactate
LC	Lactate curve
LOOH	Plasma lipid hydroperoxide
LTP	Lactate turning point
M	Metabolic conditioning
MPO	Mean power output
RPE	Rating of perceived exertion
PC	Protein carbonyl
SD	Standard deviation
TL	Training load
VO_2	Oxygen uptake
VO_{2max}	Maximal oxygen uptake
WanT	Wingate anaerobic test
W	Weightlifting
WHO	World Health Organization
WLA	Weightlifting athletes
WOD	Workout Of the Day
WU-Part	Warm-up training part of a 1-h training session

1 Introduction

1.1 Motivation and Problem Statement

CrossFit®'s international competition, the 'CrossFit® Games', considers being the ultimate fitness test worldwide and awards annually 'The Fittest on Earth®' for several years (1). Since it has always been a human endeavor to compete in contests, discovering the attention the culture of CrossFit® has achieved in a short period of time by crowning the fittest people is not surprising (2, 3). In addition, individual case reports of how the concept of CrossFit® has improved health or changed lives are increasing (4), however, scientific evidence is still missing. Initially, the workouts are supposed to prepare soldiers and police officers, as well as firefighters, to maximize their physical abilities for the required operations (5). As a result, the training concept is also already applied by several military or police departments (6-9). Given the fact that these professionals demand multisided physical skills to survive, emphasizes the motivation of understanding the principles of CrossFit®. Thus, how to become 'The Fittest on Earth®' and why the CrossFit® training concept functions, as well as narrative reports prove, is still poorly understood. In this context, it's also important to consider what impact a training program - developed to maintain fitness among elite soldiers - may have by achieving widespread public acceptance and popularity. However, the research on the physiological principles, prediction of performance, and other challenges within the sport of CrossFit® is still at the beginning, so this thesis will increase the scientific knowledge of the new training concept.

1.2 Relevance of Understanding CrossFit®

The origins of CrossFit® date back to G. Glassman, who developed the methodology in the late nineties (10). In the following, the training concept was trademarked and CrossFit® became a company (CrossFit® LLC) (11). Since then, CrossFit® has grown rapidly into a popular and successful functional fitness training (FFT) program with approximately 15,000 official CrossFit® affiliates around the world (10, 12). Meanwhile, according to the official CrossFit® website, there are affiliated training centers in 162 countries across seven continents, after G. Glassman opened the first in 2001 in Santa Cruz, California, United States (12). However, CrossFit® is more than just a training program: it's a brand that also connotes a lifestyle for many people. In this manner, the structure is composed of a central branded organization and a network of licensed affiliates (11). The CrossFit® LLC licenses the term 'CrossFit®' to training centers for an annual fee and certifies trainers (5). As a result of the fast-growing corporate chain, the company resides now in the same size range as 'Domino's Pizza' (18,848 number of locations in 2021), 'Pizza Hut' (18,381 number of locations in 2021), and 'Dunkin´ Donuts' (13,137 number of locations in 2019) (13-15). However, in order to legitimately use the term CrossFit®, the training is required to be performed at an official, affiliated training center and incorporate the principles (training content and programming) developed by the brand, as well as administered by a certified CrossFit® trainer (16). The application of the principles of the CrossFit® trademark in the context of scientific research similarly demands compliance with the terms of use[1]. So, scientific investigations exploring the actual nature of the CrossFit® LLC brand, including training at affiliated training centers, official classes and/or workouts, and involving a certified CrossFit® trainer are limited (17). Nevertheless, today millions of people practice CrossFit® (18). Thus, the growth of the brand revolutionized the fitness world. Prior to this trend, no other type of training turned into a multi-million-dollar industry as quickly, surpassing the growth of the world's largest fitness franchises, like Planet Fitness or Anytime Fitness (19). Given the current size of the company, it was evident that the unpredictable crisis of this time also has a substantial impact on the sport of CrossFit®. As a result, thousands of CrossFit® athletes around the world were forced to adapt their training behavior to the restrictions resulting from the combat against the spread of the SARS-CoV-2 virus since the end of 2019 (20, 21). So, through the massive consequences of the COVID-19 pandemic, the practice of CrossFit® may also have changed and progressed. However, at this point, sports science of CrossFit® is still in its infancy, although the number of people practicing CrossFit® is constantly increasing, even in challenging times of a global pandemic (22). One reason is that the concept applies an open-source model for the distribution of CrossFit® content, which represents a commercial innovation (23). Thereby, the official CrossFit® training guide identifies the methodology as "evidence-based fitness", supported by the founder's experience and online available data (5). In this regard, the company's main intention may be to sell the training concept with euphonious claims, rather than to prove the program's validity based on scientific principles. At this point, the scientific research on CrossFit® takes place, which intends an independent scientific evaluation of the training method. Since the relevance of analyzing the CrossFit® phenomenon is obvious, this thesis contributes to fill specific research gaps on major challenges of the science behind CrossFit®.

[1] The following research projects in this thesis fulfill the requirements, as the project supervisor Annette Schmidt is a CrossFit® Level 2 trainer and the owner of a military affiliate, so she is allowed to use the term CrossFit®.

2 Theoretical Background

2.1 What is CrossFit®?

2.1.1 The Idea of a Broad, General, and Inclusive Fitness

First, the basic principle underlying the training concept of CrossFit® is explained in more detail. So, the concept was developed prompted by the question of which physical skills generally lead to a performance advantage in every conceivable athletic task. Consequently, the target of the CrossFit® training program is to build up a broad, general, and inclusive fitness across sports disciplines. (24). Thus, according to the official 'CrossFit® Level 1 Training Guide', CrossFit® consists of a core strength and conditioning program designed to prepare athletes for any physical contingency – i.e., for 'the unknown and the unknowable' (5). For this reason, the FFT program emphasizes constantly varied functional movements executed at high-intensity and combines elements of strength, gymnastics, and endurance (25). Functional movements consist of multi-planar and multi-joint locomotor sequences that shift body weight or external objects quickly across distances. In contrast to isolated exercises, these movements involve the entire body and universal motor recruitment patterns (17, 26). As the training concept is intended to increase work capacity across multiple periods and domains, the physical demands of CrossFit® training are wide-ranging and vary constantly (5). Thus, the modality includes the development of strength, agility, and cardiovascular fitness in both periodization and individual training sessions (5, 17, 27, 28). Within the idea of CrossFit®, an increase in performance capacity across unknown athletic tasks is defined as the highest achievable form of fitness enhancement prior to any other fitness metric, e.g., body composition, flexibility, lactate threshold, strength, or maximal oxygen uptake (VO_{2max}) (25). Therefore, CrossFit® utilizes four different models to evaluate fitness (5). Together, the definitions discussed below represent CrossFit®'s understanding of comprehensive fitness.

TEN GENERAL PHYSICAL SKILLS

The first model is based on diverse physical skills. Thus, the training principle ensures general improvement of fitness by equally increasing physical performance in ten areas: (i) cardiovascular/respiratory endurance, (ii) stamina, (iii) strength, (iv) flexibility, (v) power, (vi) speed, (vii) coordination, (viii) agility, (ix) balance, and (x) accuracy (24). Optimal physiological competence may arise solely from the interaction of these abilities.

In this regard, the training program attempts to compromise on the development of each of the ten physical adaptations (5). As a result, one characteristic of CrossFit® athletes is to train non-specialized.

THE HOPPER-MODEL

The performance of athletic tasks is the focus of the 'Hopper'-Model. The underlying principle is that comprehensive fitness should enable athletes to accomplish any unpredictable physical demands. For this purpose, a lottery wheel (or a 'Hopper') is loaded with an infinite number of physical tasks, and a challenge is drawn randomly from them. Thereby, the 'Hopper'-Model states that fitness is measurable by the athlete's ability to deal with any of these physical tasks in relation to others (5). Consequently, the intended fitness of CrossFit® athletes implicates the ability to cope best with any random challenge, even with unfamiliar physical efforts. This concept constitutes also the basis of CrossFit® competitions (1, 28), see **chapter 2.1.5**.

METABOLIC PATHWAYS

Of particular interest to the third assumption of fitness are the three energy systems (phosphagen, glycolytic, and oxidative) used in human action (29). The fitness achieved by CrossFit® training involves competency in each of these three energy-delivering systems. Thought the combination of activities and exercises that predominantly target one pathway, the training program intends to accomplish a balance between each of the three (5). For example, the used energy for 1-repetition maximum (1-RM) of the back squat is provided mainly by the phosphagen (30), the energy for short runs by the glycolytic (31), and for longer activities (> 75 s) by the oxidative pathway (32).

SICKNESS-WELLNESS-FITNESS CONTINUUM

Furthermore, the fourth definition of fitness employs health markers as a measure of fitness. Since many markers can be classified on a scale from sick to healthy to fit, the CrossFit® methodology assumes that health correlates with fitness (5). The resting heart rate in beats-per-minute (bpm), for example, ranges from > 100 (high), 60-100 (normal), to < 60 (low), see **Figure 1.** Idea of a disease-wellness-fitness continuum in terms of the CrossFit® definition of fitness (5, 35). Thereby, an abnormal rate above 100 bpm increases the risk of cardiovascular disease, stroke, or early death, and a lower resting heart rate indicates a higher degree of fitness (33, 34). Thus, a training program that does not promote health stands in contradiction to the CrossFit® principles (35).

Figure 1. Idea of a disease-wellness-fitness continuum in terms of the CrossFit® definition of fitness (5, 35).

Note. The figure is adapted from the CrossFit® Level 1 Training Guide. © Copyright CrossFit®, LLC 2022. All Rights Reserved.

2.1.2 Procedure and Content of CrossFit® Training

As a result, the training program has developed characteristic workout content to achieve the goals of promoting health, training all energy delivery systems, preparing athletes to cope with any conceivable tasks, and after all, achieving comprehensive fitness (5).

METABOLIC CONDITIONING

Since one determination of the training concept is to address all metabolic pathways, the inclusion of cardiovascular activities in the exercise routine is crucial. However, within long-period aerobic exercises, such as long-distance runs, the improvement of cardiovascular/respiratory endurance and stamina is often accompanied by a decrease in muscle hypertrophy, strength, and power (36). As a result, predominantly aerobic workouts do not meet the CrossFit® program's commitment of building comprehensive fitness with equally distinctive physical abilities (5). In contrast, high-intensity exercise routines improve both the anaerobic and aerobic energy-supplying systems, whereas moderate-intensity aerobe training simply enhances maximal aerobic performance (37). For this reason, the CrossFit® training program characteristically incorporates interval training executed at a high-intensity to utilize anaerobic efforts to improve cardiovascular capacity (38). This method is commonly known as metabolic conditioning (39), and provides also the basic principle of high-intensity functional training (HIFT) or high-intensity multimodal training (HIMT), as discussed recently by Dominski et al. (17). By varying the interval patterns with different combinations (exercise, load, rest, and repetitions), all three metabolic pathways ought to be targeted optimal, resulting in an increase of anaerobic and aerobic performance, without specific adaptions to the single activity (5).

TRAINING SCHEDULE

The training sessions offered in affiliated training centers last about an hour (approximal 45-90 min) and consist commonly of warm-up and mobility exercises, skill training, in part combined with power training, the metabolic conditioning workout, and followed by a cool-down including stretching exercises as required, see **Figure 2** (5, 17, 40).

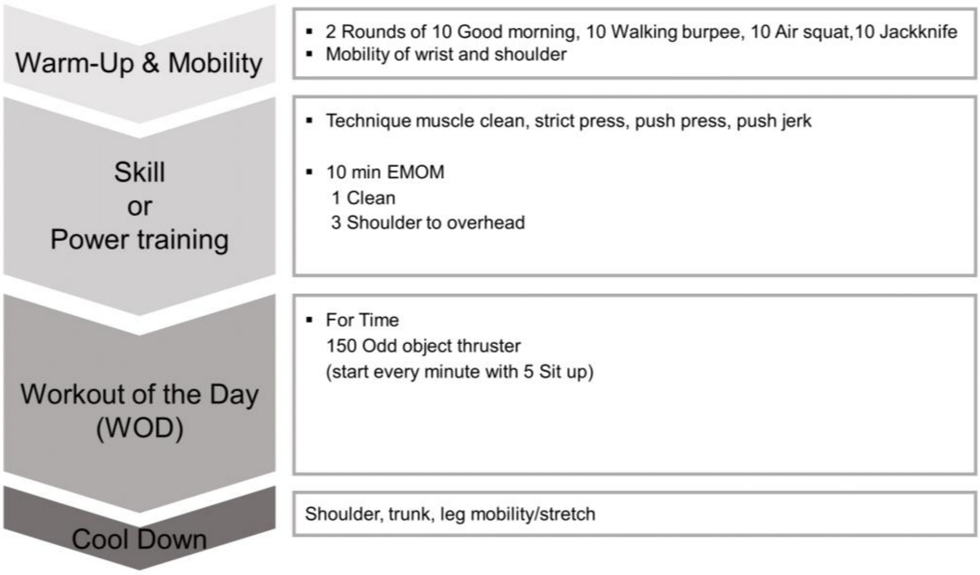

Figure 2. Sample training session programming from Brandt et al., 2022 (40).

Note. Every minute on the minute (EMOM) refers to completing the determined repetitions per exercise in the given time span and resting for the remaining time of the interval.

The warm-up and mobility part specifically prepares the athletes for the content of the training session in order to ensure minimum risk of injury at maximum intensity (41). Following this, there is either skill or power development training. This part is intended to build the basis for improving the performance of specific exercises and resistance training (5). An integral element of each training session is the metabolic conditioning workout performed at high-intensity in the last part of the training session (27, 28). The implementation of day-to-day varying functional movements in this workout constitutes the nature of CrossFit® and ensures that the athletes are constantly exposed to new challenges without being able to specifically prepare for them (24). In this way, the multimodal structure of the training program simultaneously enhances multiple fitness components, such as aerobic power and anaerobic capacity, muscular endurance, strength, and power (42).

WORKOUT OF THE DAY

Known commonly as 'Workout Of the Day' (WOD), the workouts at the end of the training session vary from day to day and are announced first on a respective day or just prior to execution (5). Thereby, the WODs consist of exercises from the main elements of gymnastics, weightlifting, and cardiovascular activities and are performed quickly, repetitively, and with little or no recovery time between sets (5, 27, 28). So, the elements of the workouts are divided based on the targeted modality: metabolic conditioning (M), gymnastics (G), and weightlifting (W), see **Figure 3** (43).

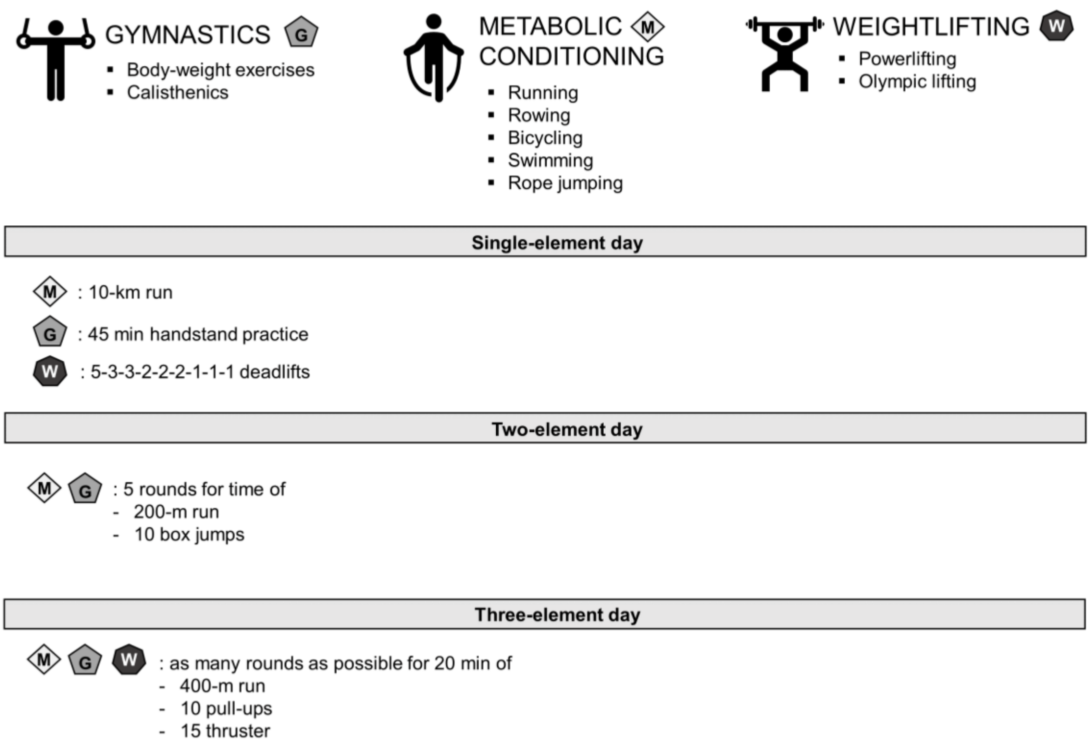

Figure 3. Overview of training elements by modality (5, 43).

Note. The figure is adapted from the CrossFit® Level 1 Training Guide. © Copyright CrossFit®, LLC 2022. All Rights Reserved.

To improve cardiorespiratory capacity and stamina metabolic conditioning activities include repetitive, cyclical movements, such as running, rowing, swimming, or bicycling. The modality of gymnastics is composed of bodyweight exercises and exercises of calisthenics and aims to enhance body control by increasing coordination, balance, agility, and accuracy, as well as increasing the functional capacity of the upper body and trunk strength. That includes exercises like air squats, pull-ups, push-ups, dips, handstand push-ups, rope climbs, muscle-ups, presses to handstands, back or hip extensions, sit-ups, and jumps. The basics of resistance training, Olympic weightlifting, and powerlifting are contained in the weightlifting modality (e.g., bench press, clean and jerk, deadlift, snatch, squat, power clean, and push press). The goal is primarily to increase strength, power, and hip and leg capacity. Exercises with additional external loads are also included in this modality (5). In summary, the content of the WODs requires that athletes perform the exercises at a high technical and strength level, however, adapted to the individual fitness ability (44). In this regard, an instrumental part of the CrossFit® training concept is also to adjust the workouts for a wide range of participants without reducing the intended training stimulus for each athlete (5).

RX OR SCALED

The WODs are usually programmed in a way that is challenging but feasible for the majority of athletes (43). Since the established parameters of the movements and weights used are not equally suitable for both genders, specific execution instructions differ for men and women (5). When a workout is performed as prescribed, it is referred to as 'RX' and the performance achieved is comparable to that of other athletes. In order to include beginners or less able participants, e.g., juniors, seniors, or anyone else who may not yet be able to complete as prescribed, the workout exercises are adapted to the individual’s ability and therefore referred to as 'Scaled' (45). In this way, also disabled athletes or older individuals are able to participate in training customized to their specific abilities without being overwhelmed by weight or time requirements. A properly scaled workout, therefore, enables participation in CrossFit® training through every fitness level (44).

TEMPLATE OF A TRAINING SESSION

The structure of the training programming is determined according to the respective modalities (M, G, or W) implemented (43). Thus, one, two, or indeed all three modalities are to be applied in a training session per day, see **Figure 3**. The official 'CrossFit® Level 1 Training Guide' provides a template for planning a two-week training routine. Thereby, the workouts on days 1, 5, and 9 consists of one single modality, while days 2, 6, and 10 each include two modalities (couplets), and days 3, 7, and 11 use three modalities in the workout (triplets). On the other days, there is rest time for recovery (5). In addition to this 3-days-on and 1-day-off structure, the training guide also suggests a 5-days-on and 2-days-off template, which may be more compatible with daily work life and weekend habits, see **Figure 4** (5).

	MON	TUE	WED	THU	FRI	SAT	SUN	MON	TUE	WED	THU	FRI	SAT	SUN
3-Days-on, 1-Day-off	M	G W	M G W	REST	G	M W	G M W	REST	W	M G	W M G	REST	M	W G
5-Days-on, 2-Days-off	M	G W	M G W	M G	W	REST	REST	G	M W	G M W	G M	W	REST	REST

G Gymnastics M Metabolic conditioning W Weightlifting

Figure 4. Overview of sequential templates of CrossFit® training programming of (5, 43).

Note. The figure is adapted from the CrossFit® Level 1 Training Guide. © Copyright CrossFit®, LLC 2022. All Rights Reserved.

Thereby, each training modality M, G, or, W is represented by a single exercise or element from metabolic conditioning, gymnastics, and weightlifting, respectively. In cases where the training is determined by one of the three modalities, it is called 'single effort' or 'single-element day', which is characterized by a long, slow session. The focus of the 'single effort' days is on practicing and training specific exercises and not on improving cardiovascular capacity. Therefore, 'element priority' is set. On a 'two-element day' or 'couplet', the training is based on two modalities, which are performed consecutively over several rounds or sets with 'task priority'. The workouts of this type are rated by the factor of completion time. Exercises are intended to be performed at moderate to high intensity, so that the first initial round of 'couplets' is hard, but feasible to complete unbroken. The following rounds or sets are supposed to be managed solely by tactically splitting the repetition sets and rest intervals. The third type, so-called 'three-element days', are 'triples' consisting of three modalities that must be repeated as many rounds as possible over a set period of time. Therefore, 'time priority' is given. The scoring of this workout occurs by counting the number of repetitions completed, wherein the fulfillment of several rounds is supposed to challenge the athletes (43). Since the training content distinguishes between element, task, or time priority, different execution instructions resulted from this, respectively 'as many repetitions/rounds as possible' (AMRAP), 'every minute on the minute' (EMOM), or 'for time' (FT). In the AMRAP mode, the maximum number of repetitions or rounds is performed in a set time interval. In contrast, in the EMOM mode, the exercise had to be performed every minute on the minute, while for the FT mode the required task must be completed as fast as possible (46). Further, the training types may provide a fixed total time limit for completion. So, in contrast to training based solely on the principles of HIFT or HIMT, which are characterized by metabolic conditioning at high-intensity, the CrossFit® training concept includes the development of power, strength, and cardiovascular fitness in a multi-functional approach (17). The specific workout content is self-designed by CrossFit®-certified coaches at affiliated training centers using templates from the 'CrossFit® Level 1 Training Guide' or is published on the CrossFit® website (5). Included are a number of standardized workouts that are used as Benchmarks for measuring the training progress of the athletes (47).

BENCHMARKS

However, due to the constant variation of training content, it is crucial to track performance variances by ascertaining the performance of specific exercises regularly. For this purpose, the Benchmark WODs are intended. They are used to monitor personal performance development by comparing the performance values (e.g., number of repetitions, time to completion, etc.) over time or with other athletes (47). Each of these WODs is standardized and performed at irregular intervals, however, each time under the same conditions. The requirements of well-known Benchmark WODs are shown in **Table 1**.

Table 1. Overview of well-known Benchmark workouts in CrossFit® (5, 47).

Benchmarks					
Girl-WODs	**Chelsea** *Every minute on the minute:* 5 pull-ups 10 push-ups 15 air squats *for a total of 30 minutes*	**Cindy** *As many rounds as possible in 20 minutes:* 5 pull-ups 10 push-ups 15 air squats	**Grace** *For time:* 30 clean and jerks (135/95 lb.)	**Fran** *For time:* 21-15-9 reps of thrusters (95/65 lb.) and pull-ups	**Helen** *Three rounds for time:* 400-meter run 21 kettlebell swings (50/35 lb.) 12 pull-ups
Hero-WODs	**Murph** *For time:* 1-mile run 100 pull-ups 200 push-ups 300 air squats 1-mile run				
Benchmark-WODs	**CrossFit® Total** *Total sum of the best from each lift:* back squat shoulder press deadlift *Three attempts for each lift*	**Fight Gone Bad** *Total Reps:* 1-min wall balls (20/14 lb.) 1-min sumo deadlift high-pulls (75/55 lb.) 1-min box jumps (24/20-inch) 1-min push press (75/55 lb.) 1-min row 1-min rest *Three rounds with a running clock*	**Filthy 50** *For time:* 50 box jumps (24/20-inch) 50 jumping pull-ups 50 Kettlebell Swings (1/0.75 pood) 50 walking lunge steps 50 knees-to-elbows 50 push press (45/35 lb.) 50 back extensions 50 wall balls (20/14 lb.) 50 burpees 50 double-unders		

Note: Weights are given in brackets, separated by gender (male/female). Workout Of the Day (WOD); Repetitions (Reps).

Therefore, the Benchmark WODs include 'Girl-WODs' (mostly short and intense workouts), which are given female names such as 'Cindy', 'Fran' or 'Helen', and 'Hero-WODs' (often long and hard to complete workouts), named after people who died while serving in the military, law enforcement, or as a first-responder (48).

THE WHITEBOARD

Another essential part of the training concept is a kind of scoreboard. This form is a documentation and information tool, which is referred to as 'the whiteboard' (5). The board used is either a classic chalkboard or a virtual platform that is displayed on a monitor screen. The training programming is written on the whiteboards every day, including the selection of exercises, execution instructions, and if required, the duration of tasks, rest periods, repetitions, and specifications of external weights used. Often, the athletes gather around the whiteboard at the start and end of each training session. At the start details of the workouts are explained and at the end, the whiteboard is used to record the results of the training (49). According to G. Glassman, the whiteboard is a useful instrument to identify relative and absolute metrics of the workouts by comparing performance with other athletes (25). In addition, online tools are also available, such as 'Wodify' or 'Beyond the Whiteboard' (BTWB), to track the performance of the athletes (23, 50, 51). By using these tools, the performance of all athletes completing the WOD on that day in the respective affiliated training center is daily reported and evaluated. Moreover, many affiliates maintain a so-called 'leaderboard', on which the best performances in common Benchmarks of the athletes are recorded (52). The leaderboard serves as a reference to demonstrate the maximum performance of a WOD and to assess individual performance. Together, the written record of the performance results is designed to encourage top performances and provide motivational support (5).

2.1.3 Relationship to Health and Life

Despite the training content, the CrossFit® program also includes nutrition recommendations and offers ways to promote health also for special populations (5). Thus, the program implements the goal of equating fitness with health. In this context, the official homepage provides the answer to the question of what CrossFit® is, with the claim "the key to health and fitness" (53). So, the program is designed to achieve multiple goals, from improving health to reducing body weight and increasing performance, and it seems to work for everyone, e.g., for disabled, injured, obese, or untrained individuals (54-58). In line with the basic principles of CrossFit®, the program thus represents a particular form of health prevention and aims to reduce chronic diseases through the training stimulus - constantly varied, high-intensity functional movement - combined with specific nutritional guidelines (35), see following.

INCLUSION OF INJURED ATHLETES AND SPECIAL POPULATIONS

To ensure that every individual benefits from the promised positive effects, the training concept offers specific methods for the participation of special populations (5). For the safest implementation of the CrossFit® program, athletes are coached and instructed by a certified trainer in small groups within an affiliated training center. Those certified trainers are qualified to employ scaling strategies for any special population: (i) beginners or deconditioned individuals, (ii) intermediate athletes, (iii) advanced athletes, and (iv) injured athletes (5). The official 'CrossFit® Level 2 Certificate Course' provides detailed scaling strategies and examples for the special demands of these participants. The main principle to consider is the preservation of the stimulus, i.e., the effect of the specific combination of the exercises (45). However, aspects of this combination can be adjusted individually, as a result, the workout has relatively similar effects on each athlete - regardless of his or her physical abilities (44). Due to the opportunities to adapt training to individual needs, a few case reports of women who have maintained their CrossFit® training even during pregnancy consequently exist (59).

NUTRITION RECOMMENDATIONS

For disease prevention and optimizing the athlete's performance, the CrossFit® program provides specific nutritional recommendations (5). The principles of nutrition and eating behavior are based on the so-called 'Zone Diet' (60). In this nutritional regime, athletes are supposed to achieve a moderate balance between carbohydrates, fat, and protein intake by tracking their macronutrients. Overall, the intended macronutrient distribution comprises 40% carbohydrate, 30% protein, and 30% fat (61). The detailed dietary prescription recommends consuming primarily the following food ingredients: lean and varied protein sources, predominantly low-glycemic carbohydrates, and fat from whole food sources. In this regard, the total amount of calorie intake is centered on the protein demand, ranging from 1.5 (moderate activity level) to 2.2 (high activity level) g/kg of lean body mass (5, 60).

In order to remain within the appropriate calorie budget and to be able to estimate the mass of meal sizes correctly, it is important to measure the individual food intake exactly. To simplify the tracking of meal consumption, the CrossFit® nutritional recommendations provide a convenient approach. In this scheme, every athlete is assigned to either 2-, 3-, 4-, or 5-block meals at breakfast, lunch, and dinner, with either 1- or 2-block snacks depending on gender and body type. Thereby, every meal and snack contains equivalent blocks of protein, carbohydrate, and fat, so a 4-block meal is composed of 4 blocks, each of protein, carbohydrate, and fat. The block chart in the 'CrossFit® Level 1 Training Guide' gives quantities of common foods equivalent to 1 block of protein (7 g), carbohydrate (9 g), or fat (3 g). The supposed meals are based on meat and vegetables, nuts and seeds, some fruit, little starch, and no sugar (5). The precise 0.75 protein to carbohydrate ratio required at each meal is claimed to reduce the ratio of insulin to glucagon, which results in a series of biological processes that reduce the risk of chronic disease, improve immunological responses, maximize physical and mental performance, and induce sustained weight loss. However, besides the low level of scientific evidence supporting the positive effects, the existing literature reviews indicate scientific inconsistencies in the Zone Diet hypothesis (60). Current scientific evidence recommended rather 5-12 g/kg body mass carbohydrates and 1.6-2.2 g/kg protein intake per day to optimize CrossFit® performance (62). Nevertheless, the consumption of known quantities and high-quality whole, unprocessed food is encouraged by the official 'CrossFit® Level 1 Training Guide' as the foundation for improved performance and health-related outcomes (5).

2.1.4 Sense of Community: What turns CrossFit® into a Lifestyle?

The combination of a healthy diet and a constantly varied, high-intensity functional exercise routine defines the lifestyle of CrossFit® athletes (63). By practicing CrossFit® in thousands of affiliates around the world, people encourage and motivate each other to achieve their goals together (2). In this regard, the CrossFit® Journal describes athletes as "pretty health-minded and disciplined individuals with a 'can do'-spirit" (64). So, besides the opportunity to enhance fitness and well-being, CrossFit® offers a social environment where one is surrounded by like-minded people who share a passion for burpees.

The underlying principle appears to be grounded in the strategy of community-building which foresees high levels of social networking and bonding (65). Through participation in CrossFit® training groups, the members receive social capital from others, including motivation, coaching, and accountability (66). The social support of the CrossFit® community builds greater self-efficacy and confidence, resulting in increased participation in the training program (67). For example, within CrossFit® training sessions, the weakest athlete often receives the most support and encouragement.

The structure of CrossFit® training groups, where athletes workout together regardless of individual fitness levels, offers opportunities to increase social support and create a social community (65). Being surrounded by people, who share the same goals promotes mutual interest in each other's progress (68). In this context, a qualitative study described the social environment of CrossFit® also as a society that embraces a variety of fitness levels, and as a result, members experience strong camaraderie, acceptance, and shared goals (66). In addition, when people feel belongingness to a group, they are more likely to adopt healthy behaviors (69). Consequently, the social interaction and environment present within CrossFit® training groups are important to the enjoyment of and adherence to the training concept (70). To the multiple factors that affect the maintenance of a CrossFit® training routine, semi-structured interviews identified the aspects of accepting and overcoming challenges, commitment, connection and community, and empowerment and transformation (71). The findings are consistent with the way the CrossFit® concept engages and extends community through a welcoming environment and relationship building, as reported in a related study (66).

Nevertheless, the culture of CrossFit® has a hybrid nature due to the mixture of elite sport and practice to promote fitness and health of the general population. Since the early days of CrossFit®, also the competitiveness with other athletes and the 'whiteboard'-mentality received great popularity from the fitness community. The training concept relies on competition with oneself and others to achieve high intensities and internal motivation (66). Thus, the employment of scoreboards (whiteboards), recording of scores and training results, and running a clock during the duration of the exercises ought to contribute to success and achieve new performance records (5). One example of the power of the CrossFit® mindset is the 'CrossFit® Open', where hundreds of thousands of people around the world work out together to test their fitness and cheer each other on. To this end, the structure of the competition is explained in more detail below (72).

2.1.5 Finding the 'Fittest on Earth®': Structure of CrossFit® Competitions

The competitive nature of the training practice also provides the basis for the competitive events of CrossFit®. So, the origin of the competitive approach dates back to the first 'CrossFit® Games' held in 2007, attended by 70 participants (28, 73). Since this date, the winners earn the title of 'Fittest on Earth®' at the annual season highlight, the 'CrossFit® Games' (1). In addition to female and male individual athletes contending for the title, competition is also held in the team division, age-based divisions for younger and older competitors (age ranges of teens include 14-15 and 16-17 years, and of masters 35-39, 40-44, 45-49, 50-54, 55-59, 60-64, and 65+ years), and eight adaptive athlete classes for competitors with physical impairments (72). So, in principle, any athlete is eligible to qualify for the 'CrossFit® Games', regardless of age, gender, or disability. To participate, the athletes so far had to pass a variety of qualification processes, such as the 'CrossFit® Open' as well as the Regionals from 2011 to 2018 in a two-stage qualification phase. In recent years several modifications to the competition's structure occurred, e.g., the regionals were removed and replaced by quarter- and semi-finals in 2021 (74). However, the changes resulted probably due to the growing popularity, reflected in the increasing number of participants, and were intended to ensure fair competition (72). Currently, the 'CrossFit® Open' represents the first level of competition, feeding subsequent rounds in the qualifying system.

THE OPEN

Thus, the 'CrossFit® Open' is considered one of the largest participatory sporting events, with more than 415,000 athletes signed up to compete in the year 2018 (72, 75). Thereby, the event consists of an annual online competition officially conducted by CrossFit® LLC, whose participants with the best online scores qualify for the next stage (72). By allowing athletes to register and be eligible to participate for a low fee *via* the CrossFit® Inc. website, the competition is easily accessible. The tasks of the 'CrossFit® Open' consists of unknown WODs (see workouts from previous years in **Appendix**) to be completed over the course of a few weeks, which were shortened from a five-week to a three-week period in 2021 (74). Participants perform the workouts and submit their results online ahead of a specified deadline *via* either videos of their workouts or validations from a CrossFit® affiliate (76). Within the CrossFit® community, the 'CrossFit® Open' has experienced worldwide popularity and approval, so the annual workouts are completed by far more athletes than actually intend to qualify for the further rounds.

THE GAMES

Following the 'CrossFit® Open', participants for the 'CrossFit® Games' are selected by competing in sequential rounds of the three-stage continental qualifying system, consisting of quarterfinals and semifinals (77). The ratings of the Open are separated by a continent, and only the best participants from each continent qualify for the quarterfinals to progress to the semifinals. At the 'CrossFit® Games', the best athletes subsequently compete in a series of workouts and activities that extend over several days. Currently, the

'CrossFit® Games' typically include 12-15 individual competitions that are held over a period of three to five days (77). As the 'CrossFit® Games' are designed as a fitness test, the content of the competitions is typically not announced prior to the event (1). In accordance with the basic principles of CrossFit®, the fittest athletes are supposed to be able to cope with any 'unknown and unknowable' task. Therefore the participants of the 'CrossFit® Games' are unaware of what to expect at the competition, see Hopper-Model in **chapter 2.1.1** (5). In fact, the attending athletes are informed about each competition task only days, hours, or even minutes in advance. In fact, at times, they are not even aware of the details of the tasks, even if they have already started to complete (28). Furthermore, in the competition often surprise elements were introduced that are not part of the typical CrossFit® training routine, like obstacle courses, road cycling, and ocean swimming (78). Also "odd-objects" (yokes, sleds, and sandbags) are involved in the workouts, a few of which athletes have not previously faced, such as the "Snail" (an object shaped like a bale of hay but partly filled with sand), or the "Pig" (a heavy block encased in rubber) (79). Given that the CrossFit® corporate claims that with the 'CrossFit® Games' the ultimate fitness test is created, this poses science to ask what can be learned from athletes completing unpredictable challenges to become 'Fittest on Earth®'.

2.2 Summary and Implications for Science

However, from the varying training routine, over the specific mentality, and the social environments among the athletes, to the unusual competitive setup, CrossFit® presents a particular training program with many facets. The implications for research include that existing knowledge from sports science may only be partially applied (28). As a result, a lack of knowledge about the underlying principles of CrossFit® reveals a number of research areas that still need to be examined (26). For this purpose, in the following, characteristic aspects of CrossFit® compared to other sports are identified.

CHARACTERISTICS AND CONTRAST TO OTHER SPORTS

The CrossFit® training routines integrate daily varying, non-specific workouts combined with nutritional recommendations (5). This strategy aims to increase physical skills and adaptations that result in an overall performance improvement. Accordingly, archiving multisided, functional fitness ought to lead to an advantage in any other physical challenges (25). So, the characteristic of non-specialization and consequently the constant variation of demands in the training concept of CrossFit® is at odds with fixed, predictable, and routine sports.

As CrossFit® combines elements of endurance and strength training, the training program is rather related to the principles of concurrent training (combination of strength exercises and classic cardiovascular activities, e.g., cycling, running, or rowing). In contrast to concurrent training, the CrossFit® concept develops endurance with a combination of these elements and by using bodyweight exercises and external weights (80). For example, the Benchmark WOD 'Grace' consist of a strength endurance activity, see **Table 1**. This type of training aims to be efficient for simultaneous improvement of strength and endurance performance without adverse effects on adaptations (81). Classic concurrent training does not include comparable approaches (82).

Furthermore, CrossFit® competitions consist of testing athletes in a variety of fitness tasks. In this regard, a characteristic element is that the WODs are not published in advance, instead of being announced close to or even during the competition (28). As a result, the athletes are unable to prepare specifically for a particular performance. The short-term announcement of the competition tasks is an important difference from other sports, where it is typically always known in detail which discipline will be held in the next contest. The unpredictability of competition underlines the need for athletes to cope with any conceivable tasks and efforts by building comprehensive fitness, consistent with the goal of FFT.

However, the common practice in affiliated training centers offers a further particularity of the CrossFit® methodology. While in most other sports training occurs separately according to the fitness level of the participants, e.g., in running groups, in CrossFit® athletes with different levels of experience can work out together in a single training session (44). The specific and individual programming of each training session and properly scaled workouts according to the ability of each trainee ensures that each athlete maintains the planned stimuli (45). As a result, the athletes experience the sense of the CrossFit® community regardless of gender, age, or physical abilities (66). In this way, a camaraderie aspect occurs, which enthuses the athletes and builds social bonds (65). In contrast to other group fitness classes where people come together to work out alone in a group setting, such as yoga or spinning classes, active participation, and interaction during CrossFit® training sessions is an essential tool in creating social connectedness (19). As a result, the lifestyle among the CrossFit® athletes and the psycho-social factors appear to be important characteristics of the new training concept compared to classical functional training.

OVERVIEW OF OPEN RESEARCH FIELDS

In summary, the CrossFit® training concept reveals several characteristic aspects that arouse the interest of scientific research. Taken together, the main interest is to understand the mechanisms of how athletes achieve the required skills and the impact of the training on the 'unknown and unknowable' (27). Furthermore, the nature of CrossFit®, whether considered as a lifestyle, as a community, as a diet, as a training routine, as a competitive sport, or as a preventive medicine intervention, together with its numerous adherents, therefore opens up a wide range of research fields (83). To date, the training principles of CrossFit® are practiced by a wide range of populations with different levels of physical fitness, including healthy individuals, obese or untrained individuals, disabled, and elite-athletes (54-58, 84). As a result, scientific interest increased since 2011, see **Figure 5**.

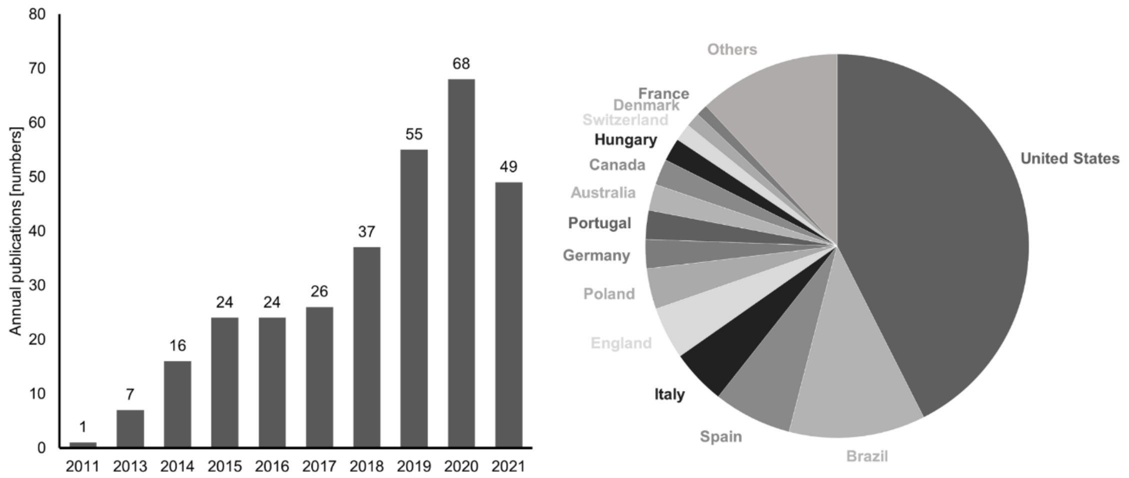

Figure 5. Numbers of scientific articles related to CrossFit® published in the years 2011-2021 and divided in percentages by country of origin.

Note. Certain data included in the figure are derived from Clarivate *Web of Science*. © Copyright Clarivate 2022. All rights reserved.

Taking a brief view of the search results of the 'Web of Science' database shows a substantial increase in the annual published articles over the last decade (85). As the systematic review by Feito et al. noted back in the year 2018, most of the conducted research continues to originate in the United States (43%), followed by Brazil (11%) and Spain (7%) in that order (83). Here the fact emerges that most of the studies are conducted in the country where CrossFit® training originated. However, considering the international adherence to CrossFit® training, a greater number of studies conducted with heterogeneous and large samples is still missing.

Due to the focus on the constant variation of the demands during CrossFit® training and competitions, existing parameters about effective methods of tracking the performance improvements of athletes in sports science are only partially usable. In this manner, a systematic review determines that CrossFit® involves individual training methods compared with the recommendations of concurrent training. Thus, existing research results only partially align with that of concurrent training (28). Understanding why the CrossFit® training program effectively improves performance and measuring how constantly varying workouts affect overall fitness skills and lead to improved performance in unpredictable tasks remains a major challenge (39, 86). Therefore, a predominant part of the scientific studies on CrossFit® is classified in the research field of physiological demands and adaptations (27). In this context, it is also essential to develop methods to monitor performance progress in CrossFit® constantly and to identify predictors that have a high impact on the physical capacity of the athletes, or to investigate what dietary or recovery strategies may improve athletic performance. In accordance, the initial systematic review by Claudino et al. identified the following research topics related to CrossFit®, classified by the authors into the categories of biomechanical adaptions, life and health aspects, musculoskeletal injury risk, and both physiological and psychological parameters (27).

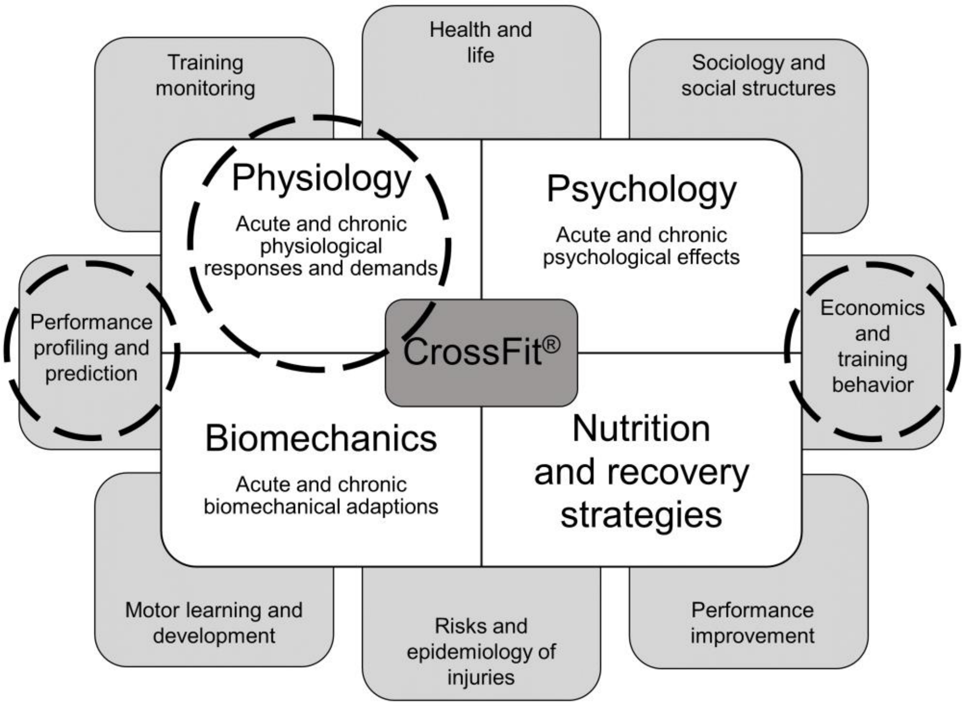

Figure 6. Compilation of the relevant research fields regarding the training program CrossFit®.

Note. Selected research areas to be explored in this thesis are marked by a dotted circle.

Indicating that issues related to social behaviors within the CrossFit® community are also of scientific interest. In this regard, a review by Dominski et al. reveals open questions concerning the following variables: motivation, enjoyment, effort, addiction, well-being and mental health, and community belongingness (87). Additional research may also consider the social structure of CrossFit®, such as team dynamics, what significant events in the past influenced the sport (issues related to sports history), or how sporting events are planned and organized (issues related to sports management). A summary of relevant open research fields is given in **Figure 6**.

However, the ongoing global COVID-19 pandemic is also affecting the sport of CrossFit® and the training habits of the athletes (20). Therefore, additional open questions arise in this area. In this context, this thesis focuses on the key research areas of (a) physiology responses, (b) performance profiling and prediction, and, for acute reasons, (c) consequences of the COVID-19 pandemic and discusses the current state of scientific knowledge below.

3 Scientific State of the Art

3.1 Physiological and Metabolic Responses of CrossFit® Training

The first topic that demands consideration are the acute physiological effects. To achieve optimal adaptations, recovery, and performance, a detailed understanding of the physiological, and metabolic demands of CrossFit® WODs are required (e.g., heart rate [HR], oxygen uptake [VO_2], and blood lactate response). For this purpose, Benchmark WODs were investigated several times to date, e.g., 'Cindy' (54, 88-92), 'Fight Gone Bad' (93, 94), 'Fran'(88, 93, 94), and 'Murph' (95). Also, other WODs known from the 'CrossFit® Open' (92, 96, 97) or commonly used (98-101) were analyzed. The summarized acute physiological responses to different CrossFit® workouts are shown in **Table 2**.

Table 2. Overview of acute short-term physiological responses to CrossFit® training.

Measures	Results	References
Blood glucose	100-120 mmol/l	(96, 97, 99, 100)
Blood lactate	6-18 mmol/l	(88, 90-94, 96, 97, 99-105)
Blood pressure	Systolic BP ↔	(99)
	Diastolic BP ↔	(99)
Heart rate	> 90% of HR_{max}	(54, 88, 89, 93, 105)
Hormonal responses	Adrenaline and Noradrenaline ↑	(103, 106, 107)
	GH ↑	(108)
	BDNF ↑	(109)
Markers of decreasing cognitive performance	Reaction and execution time ↑	(96, 97)
	Errors and omissions ↑	(96, 97)
Markers of muscle damage	IL-6 ↑	(100)
	IL-10 ↑	(100)
	CPK ↑	(101, 110)
Markers of muscle fatigue	CMJ ↓	(90, 91)
	MPO ↓	(100)
	Plank test ↓	(101)
Markers of oxidative damage	LOOH ↑	(54)
	PC ↑	(54)
Respiratory exchange ratio	> 1	(88, 102)
RPE (0-10 scale)	5.4-9.6	(54, 88, 93, 94, 101, 105)
Sweat rates	0.8-1.6 l/h	(98)
Total energy expenditure	Fran: 120 kcal	(88)
	Cindy: 260-320 kcal	(88, 89)
VO_2	55-65% of VO_{2max}	(88, 89)

Note. Arrows beside the results represent the changes post-exercise compared to pre-exercise. Blood pressure (BP); Heart rate (HR); Maximal HR (HR_{max}); Growth hormone (GH); Brain-derived neurotrophic factor (BDNF); Interleukin (IL); Creatine-phosphokinase (CPK); Countermovement jump (CMJ); Mean power output (MPO); Plasma lipid hydroperoxides (LOOH); Protein carbonyls (PC); Rating of perceived exertion (RPE); Oxygen uptake (VO_2); Maximal oxygen uptake (VO_{2max}).

The evidence focuses here on the impact of WODs with a duration of less than 10 min (88, 90, 91, 93, 101, 103, 106-108), between 10 and 19 min (91, 93, 99, 102-104, 106-108, 110) and over 20 min time (88, 91, 95). Thereby the shortest duration of the examined WODs reached a minimum of 4 to 6 min (90, 93).

Similarly, during different training modalities, e.g., AMRAP or FT, studies reported a consensus that athletes archived high blood lactate values, ranging up to 18 mmol/l, immediately after the workout (88, 90-94, 96, 97, 99-105). The highest levels of blood lactate values occurred following the WODs 'Fight Gone Bad' and 'Fran' (93, 94) and two other WODs of FT modality (101, 105). In the separate studies, significant differences in blood lactate values depending on the training modalities were determined in part (90-92, 100, 101), and in part not at all (88, 93, 110) or depending on gender (105). Performing 10 min of a triplet (consisting of three burpees, four push-ups, and five squats) and the workout 'Open 15.5' of the 'CrossFit® Open 2015' (consisting of 27–21–15–9 repetitions FT of row [calories] and thrusters [95/65 lb.]) resulted in lowest measured blood lactate levels, ranging from 5 to 6 mmol/l (96, 99). However, the blood lactate responses were comparable on average between the protocols investigated, regardless of the duration of the WODs.

Moreover, the mean HR values recorded during the training sessions were consistently high (on average 170-180 bpm) (88-90, 93, 95, 105) and reached values above 90% of the maximum HR (HR_{max}) within a brief amount of time (93), regardless of modalities (AMRAP or FT) (92, 105) or the duration of the WODs (93). These data are consistent with the mean VO_2 values, which were measured on high levels (between 55% and 65% of VO_{2max}) with a relevant duration of time spent with a respiratory exchange ratio above one (88, 89, 102). Throughout the examined WODs, the high-intensity feature was evident by high rating of perceived exertion (RPE) values (0-10 scale), which ranged on average between 5.4 (strong) to 9.6 (very, very strong, no longer works) and, remained predominantly above 7 (very strong) (54, 88, 93, 94, 101, 105). Consequently, high sweat rates and energy expenditure (13 kcal/min) was observed during the workouts (88, 89, 98). In addition, a few studies investigated hormonal (testosterone, cortisol, growth hormone [GH], insulin-like growth factor 1 [IGF-1], adrenaline, noradrenaline, and Brain-derived neurotrophic factor [BDNF]) and inflammatory responses (Creatine-phosphokinase [CPK], interleukin-6 [IL-6], IL-10, plasma lipid hydroperoxides [LOOH], and protein carbonyls [PC]) (54, 100, 101, 103, 106-110). As an acute effect, just the variables of GH, BDNF, adrenaline, and noradrenaline were consistently increased post-exercise

(103, 106-109). Further, after different CrossFit® training sessions, an increase in certain markers of muscle damage was measured, including elevated levels of IL-6 independent of WOD and IL-10 dependent on WOD programming (100). Two studies revealed that the biomarker CPK increased directly after the completion of the workouts (101, 110). Besides, CrossFit® training similarly induced an oxidative stress response comparable to a traditional bout of high-intensity treadmill running, as measured by markers of oxidative damage (LOOH, PC) (54). Muscle fatigue (measured by decreased countermovement jump [CMJ] values, mean power output [MPO], and plank time) was observed through CrossFit® training immediately post-exercise in most protocols and lasted up to 24 h after (90, 91, 100, 101). Correspondingly, prolonged reaction and execution time and an increased number of errors and omissions were also noted during the Attention Concentration Test immediately after CrossFit® training consisting of the 'Open 15.5' workout of the 'CrossFit® Open 2015' (96, 97). Since BDNF is a key biomarker that modulates neurogenesis and may be essential for cognition (111), and previous studies have shown that blood lactate produced during exercise is correlated with the release of BDNF (112), the observation of significantly enhanced peripheral BDNF levels following a CrossFit® workout at high-intensity (all-out modus) is additionally noteworthy (109).

Also, the long-term adaptations of CrossFit® workouts are recently investigated for improving the understanding of the effectiveness of the training concept. Thereby, the durations of observed CrossFit® intervention programs lasted between 4 weeks and 6 months (80, 113-119). As the main outcome of most interventions improved maximal performance in different strength exercises (bench press, leg press, back and front squat, strict press, and deadlift) was recorded (80, 116-118). Also, the performance in bodyweight exercises (pull-ups), conditioning exercises (1,5-km running), and mixed exercises (three mixed WODs) were improved through 3-6 months of CrossFit® training (117, 118). Although one study by Drake et al. showed no improvement in performance parameters, which may depend on the short 4-week observation period (115).

Furthermore, several effects on the endurance values were observed, such as increased aerobic capacity, muscle endurance, and VO_{2max} (80, 113, 116), although the reported results were not or only partially confirmed in two other studies (115, 118). Anaerobic capacity was tested with the Wingate anaerobic test (WanT), which showed a significant improvement (80, 114). As a further aspect, changes in the body composition of the athletes resulting from the CrossFit® training program were also examined. Here an increase in lean body mass, a decrease in body fat, and bone mineral improvements were observed, with a gender-dependent amount of change levels (114, 116, 117).

Alongside the long-term effects of the training concept of CrossFit®, the acute physiological reactions are essential for determining the training plan and optimizing the progression, and thus constitute a focus of this thesis (120). However, despite the WOD is usually the main part of a CrossFit® training session, in affiliated training centers the training program common consists of added parts (28). So, specific modalities, like technical skill training or resistance exercises, are often added to the basic set-up according to the training guide (warm-up, preparation, and WOD), see **chapter 2.1.2** (100). In addition to warm-up and cool-down times, parts of power training (Olympic weightlifting and powerlifting), and skill development were included in each training session in a few previous investigations (116, 117). Therefore, the training program also needs to be scientifically examined in the way the concept is conducted in practical settings. For example, the authors Feito et al. described the combination of strength and cardio parts in a single training session (117), or the authors Tibana et al. presented the following session programming: (i) strength and power exercises, (ii) gymnastic movements, and (iii) metabolic conditioning consisting of a 10-min AMRAP workout (100). Although the physiological effects of particular WODs were described in detail, there is still a lack of comprehensive analyses on the acute physiological responses of entire training sessions in the scientific literature.

Moreover, the nature of WODs ranges widely (conditioning, strength, or mixed exercises), and their duration also varies from ultra-short protocols of less than 2 min to short protocols of only a few minutes (up to 10 min), to middle protocols (10 to 19 min), and long protocols achieving a duration of 40 min and more (80, 93). Thus, an examination only of the best-known Benchmark WODs is insufficient to adequately characterize and understand the specific impact of CrossFit® workouts. The consideration of the acute, short-term physiological responses helps in selecting optimal training interventions, prevents negative interference, and is useful for evidence-based practical applications (28). So, from a physiological point of view, there is still more research to be undertaken on this kind of sport. In this regard, this thesis focuses on the acute, physiological, and cardiovascular effects of CrossFit® training and investigated, therefore, the blood lactate and HR values in response to a short CrossFit® workout lasting less than 2 min (see **chapter 5**) and during different 1-h training sessions under practical settings (see **chapter 6**).

3.2 Predictors of CrossFit® Competitive Performance and Performance Enhancement

In order to contribute to a greater knowledge of the demands of CrossFit®, international competitions and performance requirements also deserve to be examined in detail. Despite the transformation into one of the largest sports events in the world, to date, only limited numbers of studies exist on the demands for success in CrossFit® competitions, such as the 'CrossFit® Open' or 'CrossFit® Games'. Due to the lack of knowledge, it is unable to provide a consensus of performance-determining factors of CrossFit® WODs as in the case with other individual or team sports (121, 122). The level of performance in common sports (i.e., running, basketball, football, etc.) is usually quantified either by the athlete's performance on the field or is implied by the athlete's level of competition and years of experience (123). In contrast, however, the wide-ranging and until last unknown demands of the competition-WODs, the changing nature of the past competitions, as well as the limited opportunity for athletes to gain specific competition experiences, make it challenging to assess and identify trainable characteristics and success predictive factors. Nevertheless, research-based evidence exists on the identification of appropriate predictor values that influence sports performance in CrossFit®. This research aims to develop recommendations for effective and specific training programming that resulted in optimal competitive performance and performance enhancement. In this regard, **Table 3** provides an overview of the parameters that significantly predict or are correlated with CrossFit® performance. For this purpose, the majority of the studies focused on determining variables associated with performance or ranking at the 'CrossFit® Open' or 'CrossFit® Games' held in the years 2016 (124, 125), 2017 (126), 2018 (127), 2019 (128-130), and 2020 (74, 131). Additionally, the common Benchmark performances ('Cindy', 'Grace', 'Fran', and 'Murph') (95, 129, 132-135) as well as other usually performed WOD modalities (AMRAP or FT) were investigated (104, 120). Thereby, the sample size ranged from 10 to 32 participants when experimental measurements were used for data collection (95, 104, 120, 124, 126-129, 131-137), and with the use of data available online (125) or reported data from questionnaires (130, 138), the sample size went up to 3,000 (139). However, upon further consideration, it is unfortunately noticed that approximately half of the experimental data acquisitions only include male athletes in the investigation (74, 95, 120, 126, 128, 130, 134-137), which certainly affects the generality of the conclusions that can be drawn from the results.

Table 3. Overview of predictors for the performance outcomes in CrossFit® athletes.

Study design	Sample (gender)	Predictor	Predicted performance	R-Squared (R^2) or correlation coefficient [a] (r)	Reference
Experimental data	Eleven CrossFit® Open competitors (male = 5; female = 6)	Average round rate of a workout with multiple rounds (reps · s^{-1})	2016 CrossFit® Open 16.2 2016 CrossFit® Open 16.5 2016 CrossFit® Open 16.1	$R^2 = 0.99$ $R^2 = 0.94$ $R^2 = 0.89$	(124)
		Slowest round rate of a workout with multiple rounds (reps · s^{-1})	2016 CrossFit® Open 16.3	$R^2 = 0.94$	
		Wall ball completion rate of a one round workout (reps · s^{-1})	2016 CrossFit® Open 16.4	$R^2 = 0.89$	
Experimental data	Sixteen experienced (> 2 years) athletes (male = 8; female = 8)	Body fat percentage (%)	2018 CrossFit® Open 18.1 2018 CrossFit® Open 18.3 2018 CrossFit® Open 18.2a	$R^2 = 0.89$ $R^2 = 0.62$ $R^2 = 0.55$	(127)
		Body density (kg · l^{-1})	2018 CrossFit® Open 18.4 2018 CrossFit® Open 18.5	$R^2 = 0.77$ $R^2 = 0.67$	
		Vastus lateralis cross-sectional area (cm^{-1})	2018 CrossFit® Open 18.2b	$R^2 = 0.78$	
Experimental data	Fifteen male amateur CrossFit® athletes	RSI ($cm \cdot ms^{-1}$), SJ (cm) and VO_{2max} ($ml \cdot kg^{-1} \cdot min^{-1}$)	Performance of the 2019 CrossFit® Open [b]	$R^2 = 0.81$	(128)
Experimental data	32 males (experienced CrossFit® athletes = 21; beginner group = 11)	Age (years), CrossFit® experience, WanT (watt) and VO_{2max} ($ml \cdot kg^{-1} \cdot min^{-1}$)	AMRAP workout (12 min)	$R^2 = 0.80$	(120)
		CrossFit® experience	FT workout (21-15-9)	$R^2 = 0.59$	
Experimental data	29 physical-active adults (male = 15; female = 14)	Repeated WanT performance	AMRAP workout (15 min)	$R^2 = 0.74$	(104)
Experimental data	Fourteen experienced CrossFit® athletes (male = 10; female = 4)	Total-body strength (CrossFit® Total in kg)	Grace Fran	$R^2 = 0.77$ $R^2 = 0.42$	(132)
Experimental data	Seventeen experienced CrossFit® athletes (male = 12; female = 5)	VO_{2max} ($ml \cdot kg^{-1} \cdot min^{-1}$)	Nancy	$R^2 = 0.68$	(133)
		WanT (watt)	CrossFit® Total	$R^2 = 0.57$	
		Back squat (kg)	Fran	$R^2 = 0.42$	
Experimental data	Seventeen trained males	Total-body strength (CrossFit® Total in kg)	Grace	$R^2 = 0.62$	(134)
Experimental data	Twenty trained males	Back squat (kg)	Performance of the 2017 CrossFit® Open [b]	$R^2 = 0.42$	(126)
		Back squat (% of body mass)	Performance of the 2017 CrossFit® Open [b]	$R^2 = 0.38$	
Experimental data	Twenty-two trained participants (male = 13; female = 9)	VO_{2max} ($ml \cdot kg^{-1} \cdot min^{-1}$)	2019 CrossFit® Open 19.1 (scaled)	$R^2 = 0.39$	(129)
		Total-body strength (CrossFit® Total in kg)	Fran (modified)	$R^2 = 0.33$	
Experimental data	Seventeen experienced CrossFit® athletes (male = 11; female = 6)	Tibana test (reps)	2020 CrossFit® Open 20.5 2020 CrossFit® Open 20.2 2020 CrossFit® Open 20.3 2020 CrossFit® Open 20.1 2020 CrossFit® Open 20.4	r = - 0.89 (r = - 0.63)[c] r = 0.83 (r = 0.98)[c] r = 0.74 (r = 0.71[n.s.])[c] r = - 0.73 (r = - 0.96)[c] r = 0.51[n.s.] (r = 0.84)[c]	(131)

Table 3. (continued).

Study design	Sample	Predictor	Predicted performance	R-Squared (R^2) or correlation coefficient [a] (r)	Reference
Experimental data	Eleven male CrossFit® athletes	Body fat percentage (%)	Murph	r = 0.71	(95)
Experimental data	Fifteen male CrossFit® amateur athletes	Maximum reps of thrusters	Fran	r = - 0.82	(135)
		2,000-m row (s)	Fran	r = 0.67	
		Thrusters (kg)	Fran	r = - 0.61	
		Maximum reps of pull-ups	Fran	r = - 0.60	
Reported data by questionnaire	Twenty best male Czechs in the CrossFit® Open 2019 ranking	Snatch (kg)	Ranking in the CrossFit® Open 2019	r = - 0.61	(130)
		Clean & Jerk (kg)	Ranking in the CrossFit® Open 2019	r = - 0.63	
Use of public data	80 CrossFit® Games 2016 finalist (male = 40; female = 40)	Fithy 50 (s)	Ranking in the CrossFit® Games 2016	r = 0.77	(125)
		400-m sprint (s)	Ranking in the CrossFit® Games 2016	r = 0.69	
		Snatch (kg)	Ranking in the CrossFit® Games 2016	r = - 0.42	
		Clean & Jerk (kg)	Ranking in the CrossFit® Games 2016	r = - 0.39	

Note. [a] Pearson's resp. Spearman's correlation coefficient
[b] Overall performance of the 'CrossFit® Open' (i.e., summing the final score of all WODs)
[c] Values for women are given in brackets if the correlation coefficients are separated by gender
[n.s.] not significant
The Tibana test (local muscle endurance test) consists of four following rounds with 2 min of rest between the rounds: 4 min of as many rounds as possible (AMRAP) of five thrusters, and 10 box jump over (round 1); 4 min of AMRAP of 10 power cleans, and 20 pull-ups (round 2); 4 min of AMRAP of 15 shoulder-to-overhead, and 30 toes to bar (round 3); and 4 min of AMRAP of 20-calorie row, and 40 wall balls (round 4).
Abbreviations: For time (FT); Repetitions (reps); Relative strength index (RSI); Squat jump (SJ); Maximum oxygen consumption (VO_{2max}); Wingate Anaerobic Test (WanT).

Overall, the studies aim to determine factors that are significantly correlated with CrossFit® performance or that explain most of the variance by using Pearson's resp. Spearman's correlation (95, 125, 130, 131, 135), linear resp. multiple regression analysis (104, 120, 124, 126-129, 132-134), or principal component analysis (136, 137). Interestingly, different pacing strategies for how to approach the challenges of the '2016 CrossFit® Open' explained the most variance, suggesting that when the WODs consist of multiple rounds, competitors may employ a fast and sustainable pace to improve performance, and otherwise focus on one or two key exercises is recommended (124). In Addition, the latest studies on predicting CrossFit® performance indicate that physiological parameters and high-level competitive experience influence more than one specific fitness marker (95, 120, 127). In this context, the results of different authors are also consistent, which investigated the relationship between Benchmark WODs ('Cindy', 'CrossFit® Total', 'Grace', 'Fran', 'Murph', and 'Nancy',) and selected performance parameters (95, 132-136). The data show that it is impossible to determine exactly which individual fitness marker (e.g., pull-ups, back squat, snatch, clean & jerk, 400-m sprint, or 2,000-m row) is most important to achieve the best results in any WODs (125, 126, 130, 133-135). Nevertheless, depending on the nature of the Benchmark WODs a strong total-body strength (i.e., CrossFit® Total performance) indicates to be useful for higher workout scores (129, 132, 134). Further, the authors discussed the influence of physiological parameters on the performance of common WODs or of the 'CrossFit® Open' (95, 104, 127-129, 133). The correlations revealed the strongest association in increased performance with body composition (95, 127, 137), followed by aerobic capacity (VO_{2max}) (128, 129) and anaerobic power (WanT performance) (104, 133). After the body fat percentage (or body density) was the most important factor for success in the '2019 CrossFit® Open', it seems suitable to maintain a healthy ratio of fat mass to lean mass to maximize performance (127). However, CrossFit® experience seems to assume increasing importance, as the findings of Bellar et al. suggest that experience is a more consistent predictor of performance than physiological measures (120). In particular, under competition conditions, the results of two studies by Mangine et al. also highlight that participation (i.e., experience in CrossFit® competition) and ranking in previous 'CrossFit® Open' were the most common predictors of the 'CrossFit® Open' performance in the years 2018, and 2020 (74, 127).

Related interesting approaches are special testing methods especially developed for HIFT to predict the performance of the athletes (104, 131). So, the authors Feito et al. note that the ability to quickly recover between high-intensity exercise units, as measured by WanT, is positively related to performance in a 15-min AMRAP workout (104). For the same reason, the authors Tibana et al. applied a specific local muscle endurance test (named Tibana test) consisting of four following rounds with 2 min of rest between the rounds: (i) 4 min AMRAP of five thrusters, and 10 box jump over, (ii) 4 min AMRAP of 10 power cleans, and 2 pull-ups, (iii) 4 min AMRAP of 15 shoulder-to-overhead, and 30 toes to bar, and (iv) 4 min of AMRAP of 20-calorie row, and 40 wall balls. The application demonstrated that the Tibana test and strength were strongly related to 'CrossFit® Open' workout performances in 2020. However, in contrast to previous studies, body fat percentage (95, 127) and cardiorespiratory capacity (128) were not significantly correlated (131). Self-reported data of a large sample (n = 3,000) were compared based on their performance profile, and significant differences were observed between the quantiles created. With improved overall performance, strength skills (back squat, deadlift, strict press, snatch, clean & jerk) increased significantly, while no development was shown in aerobic (5-km running) or mainly anaerobic exercises (400-m sprint) (139). Another factor influencing performance enhancement and mentioned in CrossFit®-related scientific literature concerns also the sleep quality of the athletes. A survey of 149 participants showed that CrossFit® athletes with high sleep quality (determined by Pittsburgh Sleep Quality Index) reported higher scores on all performance-related outcomes, particularly in the 'Hero-' and 'Girl-WODs' (138). However, before participation in competitions, a determination of a performance profile also is essential to ensure that CrossFit® athletes are able to assess their ability progress even during the training. This allows athletes to rank their performance, assign their specific performance level, and identify deficiencies. Nevertheless, an objective assessment of CrossFit®-specific performance is challenging as normative data are still poorly available. To date, only one approach tried to develop normative values for five common Benchmark workouts (i.e., 'Fight Gone Bad', 'Filthy 50', 'Fran', 'Grace', and 'Helen') by self-reported data of 10,000 randomly selected profiles of more than 130,000 athletes (140). Nevertheless, in the majority of investigations, the surveys were conducted among athletes from the same geographical location (e.g., analysis of the best Czech CrossFit® athletes by Schlegel et al. (130)), and to date, no research has evaluated any country-specific differences in CrossFit® performance or analyzed regional factors influencing performance in competition. Since it is known from other sports that, for example, European soccer teams are most successful and more frequently represented in international competitions (141), further research is required on regional differences in competitive performance. Considering the fact that CrossFit® was born in the United States, it is assumed that American athletes have an advantage in CrossFit® training and competition experience compared to other athletes, which may affect the scientific performance prediction.

However, only restricted data are available to guide athletes in identifying the most important parameters to focus on during training and competition preparation. As there is limited evidence and no consensus on which characteristics and predictors are most relevant, the athletes must still train 'the unknown and the unknowable' (136). Deciding what parameter athletes might focus on is further complicated by their CrossFit® experience, their current level of competition, and each specific fitness ability. Thus, the preparation of athletes for the unpredictable demands of future competitions remains a major challenge for CrossFit® science. In this context, this thesis includes a determination of a CrossFit® performance profile consisting of the common Benchmark in power lifts, Olympic lifts, running times, and three 'Girl'-WODs, and followed an investigation of performance predictors using the obtained data, see **chapter 7**.

3.3 Challenges for the Sport of CrossFit® in Consequence of the COVID-19 Pandemic

Since the end of 2019, however, the entire world furthermore faces the gravest and unprecedented crisis of this time so far, both health-related and economic. Thus, with the rapid spread of the SARS-CoV-2 virus, society was quickly confronted with the challenge of coping with a global pandemic (142). Certainly, this fact has a notable impact on the sport of CrossFit® and influences the training behavior of thousands of athletes.

The World Health Organization (WHO) declared on the 30th of January 2020 that the new coronavirus outbreak is a public health emergency of international concern (143). Even within a few months, the virus has spread around the world, reaching Australia, Germany, Japan, and the United States (144). The characteristic of the novel coronavirus compound is that it is active spread by close contact, with transmission routes including direct transmission (coughing, sneezing, and droplet inhalation) and contact transmission *via* the mucous membranes of the mouth, nose, and eyes (145). So, after only 6 months of the virus outbreak, the SARS-CoV-2 virus has infected over 10 million people worldwide, resulting in over 500,000 confirmed deaths (146). The outbreak and rapid spread of the virus caused the governments of several countries to undertake early preventive interventions (147, 148), which included, e.g., lockdown of cities (149), travel warnings and cancellations (150), social distancing regulations (151, 152), and the closure of schools and all non-essential businesses (153). In particular, these restrictions extended in part to closures of CrossFit® gyms and training facilities, depending on the individual countries' strategies (154). For the first time since the beginning of the sport of CrossFit®, athletes were faced with the unprecedented challenge of not being able to perform their sport as usual in their familiar environment with regional differences in access to training facilities (154, 155).

Nevertheless, the WHO recommended staying physically active, especially during the COVID-19 pandemic, to maintain optimal health (156, 157). This is confirmed by a review article that provides that moderate-intensity training is able to enhance the immune system and negate the negative effects of obesity and physical inactivity during the COVID-19 pandemic (158). So far, however, research on how CrossFit® athletes adapt their training during quarantine or lockdown periods and whether their sports schedule impacts physical and health-related outcomes is limited.

In total, to date, only three studies investigated the consequences of the COVID-19 pandemic in relation to the sport of CrossFit® (20, 21, 159). The purpose of the first study by Redwood-Brown et al. was to establish whether habitual CrossFit® participation is associated with lower body mass index (BMI) values during the United Kingdom's nationwide lockdown and to further investigate how habitually trained CrossFit® athletes perceive their COVID-19 susceptibility (20). The main findings of the online survey (n = 1,806) indicated that self-reported CrossFit® participation (measured in minutes of exercise) during the first UK lockdown, was indicative of a lower BMI, which is associated with increased immunity against viral infections (160), and that athletes did not consider their training history to impact the probability of infection with the SARS-CoV-2 virus. Furthermore, the results provide a rare insight into the training behaviors of CrossFit® athletes during a period of national lockdown. Over 45% of participants declared that their training habits remained unchanged, and more than 50% reported that their mental well-being did not change during this period, although the literature suggests that the restrictions imposed by the COVID-19 pandemic may have significant effects on an individual's mental health (161). The authors discuss their observations that the maintenance of psychological well-being and habitual training during lockdown is related to a strong sense of community (social bonds) by the CrossFit® training concept (20, 65).

As well, the outcomes of Araujo et al. reveal that most (98.5%) of the participants were able to continue with CrossFit® training and physical exercise routine at home during times of social distancing, even in small environments, such as a balcony (21). Nevertheless, a decrease in training intensity was noted in 64% of the respondents, as shown by bodyweight exercises, such as air squats (98.2%) were mostly performed. Using an online questionnaire (n = 197), this study aimed to compare the prevalence of urinary incontinence before and during the COVID-19 lockdown of Brazil in women practicing CrossFit® and showed a reduction from 32% to 14% between before and during the lockdown. Thus, the authors concluded that the forced reduction of training intensity led to a decrease in the prevalence of urinary incontinence among female athletes.

Furthermore, a project by Cataldi et al. investigated how to mitigate the fitness deficits of Italian adolescents (n = 30) by practicing regular and traditional physical exercises caused by the COVID-19 prevention efforts resulting from the combat against the spread of the virus (159). By the suspension of any social events, and activities practiced in gyms, and closing them, the Italian government encouraged social distancing, which inhibited group motor activities and team sports in the school environment (162). To counteract this fact, the effectiveness of an 8-week CrossFit® program on physical fitness and psychophysical well-being was evaluated during the period of lockdown. The findings present that the CrossFit® intervention program positively affects the general physical fitness and mental attitude in healthy adolescents compared to a control group (159).

Despite the novel findings of the referred research concerning the impact of the consequences of the COVID-19 pandemic on CrossFit® training behavior and execution, many questions remain unanswered to date. Although Redwood-Brown et al. report that training behavior may have not changed for about half of the surveyed (20), the question arises as to what has occurred along the other half of participants, in health-related and physiological aspects. How the changed training habits during the lockdown periods are represented in detail and what consequences of the COVID-19 pandemic result for the athletes and the sport of CrossFit® have not yet been evaluated due to the altered focus of the previous studies. In addition, an upward trend in the participation and availability of online sports offers and online competitions has been observed since the years of the COVID-19 pandemic (163). For example, the responses to pandemic-related changes of the CrossFit®-similar sport weightlifting were investigated in six countries (Australia, Canada, Germany, Spain, United Kingdom, and the United States) and the results indicated pandemic affected weightlifters in different countries unequally, with a larger impact on sport and physical activities in Europe. However, the athletes found new ways to train, including at home, using online tools, and were motivated to participate in virtual competitions (154). Consequently, the training behavior of CrossFit® athletes is assumed to undergo changes during the SARS-CoV-2 lockdown as well, influenced by the access to equipment at home and the offering of digital sports.

As combating the spread of the SARS-CoV-2 virus challenges societies across different countries, the consequences of the interventions are still in part unclear and unpredictable to date. In addition, a major challenge for science in relation to CrossFit® sports, therefore, continues the review of the implications of the unprecedented crisis of this time. To this end, **chapter 8** addresses how CrossFit® athletes dealt with the closure of affiliated training centers as part of the nationwide lockdown in Germany (164).

4 Aims and Outline of the Studies in this Thesis

Despite the few numbers of previous studies on the CrossFit® training concept, scientific research is still confronted with many open questions regarding the new training program. To become the 'Fittest on Earth®' and build comprehensive fitness, soldiers, or firefighters demand, it is important to understand the basic principles of CrossFit®. This allows to optimize the training process and to avoid possible interference (28). However, there is an ongoing lack of knowledge regarding the sport of CrossFit®. So, depending on the current scientific state of the art, the overarching aim of this thesis is to address multiple research topics in parallel and summarize a series of studies on major challenges to fulfill specific research gaps faced by the science of CrossFit®. As a result, this thesis obtains a better understanding of the principles of how the training program prepares athletes for the demands of 'the unknown and the unknowable' (5). In this context, to determine practical applications and recommendations for athletes, trainers, and sports scientists, more individual research is crucial. As a result, the objective of this thesis focuses consequently on the analysis of specific aspects in detail. After reviewing the state of scientific literature, three areas of research were selected to be considered: (a) investigating the acute, short-term physiological and cardiovascular effects of CrossFit® training, (b) determining a CrossFit® performance profile, and assessing the predictors of competitive performance and performance improvement, and (c) examining the impact of the consequences of the COVID-19 pandemic on training behavior of CrossFit® athletes and describing the way the athletes dealt with the restrictions. The pursuit of these research objectives is intended to contribute to a detailed insight into the nature of CrossFit®. For this purpose, this thesis delineated the following problem statements and developed corresponding research questions and related separate study designs. In total, four separate research approaches were conceptualized, which included two experimental trials and two online surveys. Thus, the outline and structure of this thesis are summarized in **Figure 7**.

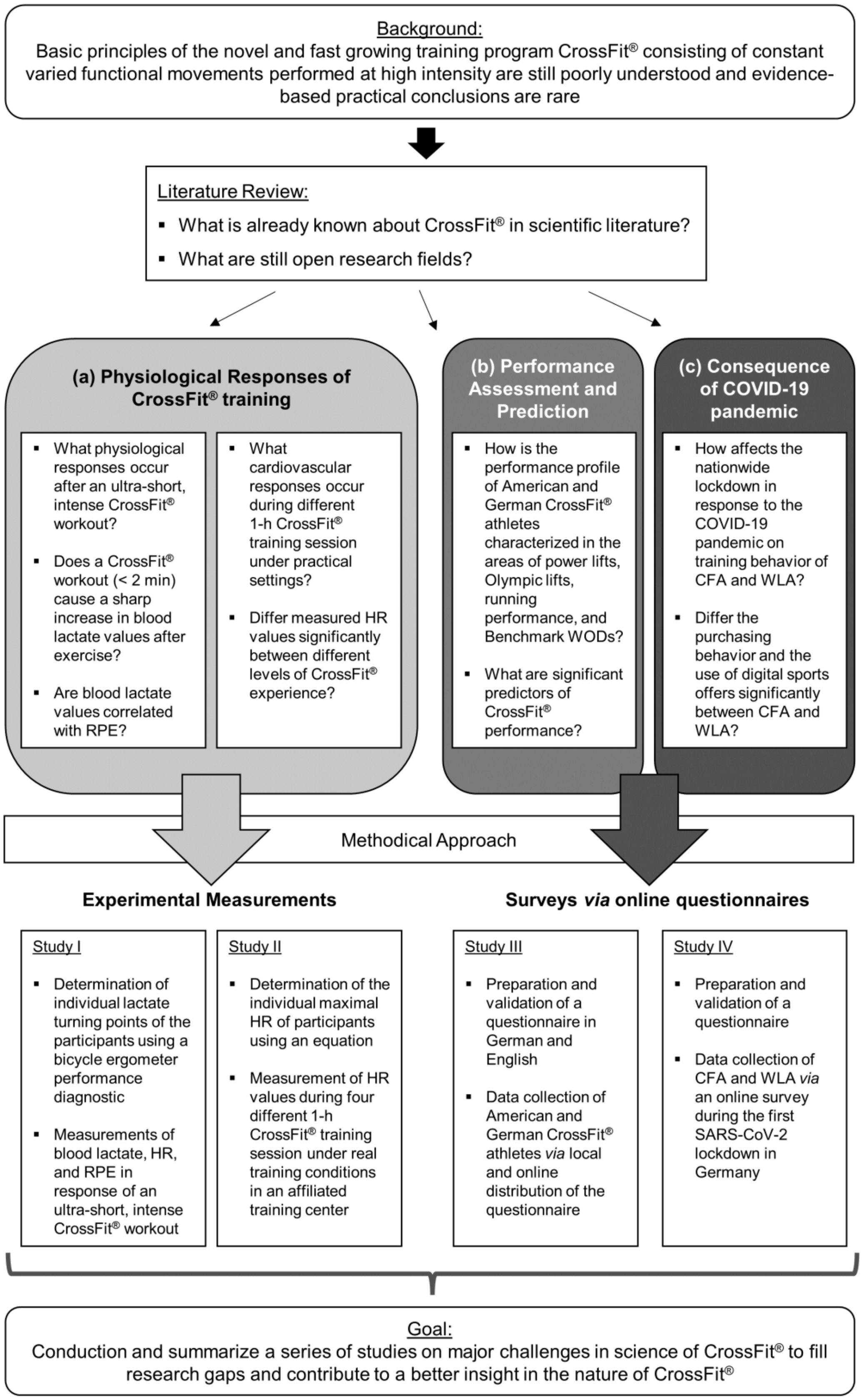

Figure 7. Overview of the structure of this thesis.

Note. CrossFit® athletes (CFA), Heart rate (HR), Rating of perceived exertion (RPE), Weightlifting athletes (WLA).

Subsequently, an overview and a short introduction of the included studies are provided, followed by the respective articles.

STUDY I

Meier, N., Thaden, T., & Schmidt, A. (2021). **Delayed Increase in Blood Lactate Concentration after a Short, Intense CrossFit® Workout**. Archives of Clinical and Medical Case Reports, 5(3), 468-478.

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Research Artikel

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Given that previous research on the physiological effects of CrossFit® training focused on common WODs with a minimum of 4 to 6 min (90, 93), raises the question, what are the physiological and metabolic responses of an ultra-short, intense CrossFit® workout? According to the current state of scientific literature, no study presents physiological parameters across a CrossFit® workout lasting less than 2 min. For this reason, an ultra-short, intense workout was chosen for the initial pilot study to analyze the physiological responses *via* an intervention study. Considering that 100-m, 200-m, and 400-m runs are known to increase blood lactate after exercise, reaching a maximum of 6-9 min after completion (165), the aim of the study is to investigate whether short CrossFit® workouts (< 2 min) can lead to similarly high blood lactate concentrations? Since CrossFit® workouts are mainly performed with high RPE levels (62), the investigation further intended to determine, whether the increase in blood lactate values correlates with RPE levels? Therefore, performance diagnostics were obtained from participants (n = 10) to determine the individual lactate turning points (LTP) using a bicycle ergometer. Consistent with the assumption that an increase in blood lactate levels is expected after completion of the exercise, measurements of blood lactate, HR, and RPE levels of the participants were analyzed immediately to 11 min after the performance of the ultra-short, intense workout consisting of 30/20-calorie Air Bike, followed by 10 repetitions devil press with 10/5 kg dumbbell for time. The obtained data demonstrate for the first time a time-delayed increase in blood lactate levels in response to CrossFit® training, with lactate levels reaching up to 4-fold of LTP2 during the post-training observation period, see **chapter 5**.

STUDY II

Meier, N., Sietmann D., Schmidt, A. (2022). **Comparison of cardiovascular parameters and internal training load of different 1-h training sessions in non-elite CrossFit® athletes.** Journal of Science in Sport and Exercise, 1-12.

https://doi.org/10.1007/s42978-022-00169-x

Research Artikel

First Online. 22 June 2022

Since previously most of the studies regarding CrossFit® investigated isolated WODs, this thesis comprised in addition an observation of cardiovascular parameters during the entire duration of a series of 1-h CrossFit® training sessions, as commonly offered at affiliated training centers (116). To date, no studies examined differences in cardiovascular responses for each part of a CrossFit® training session (warm-up part, power or skill training part, and the last part including the WOD) which is crucial due to the inclusion of distinct movements and energy delivery systems are targeted in the separate parts (28). Furthermore, the majority of previous approaches measure the physiological effects of CrossFit® training in laboratory settings (28) or isolated clinical trials, instead of in terms of how affiliated training centers implement the training program. For this purpose, this observational study intends to determine, what cardiovascular responses, measured by HR values of non-elite athletes (n = 27), occurs under real training conditions, and how different levels of CrossFit® experience impact. Following the basic principles of CrossFit® that due to scaled exercise adaptations, beginner and experienced athletes are trained in the same training session, four different training sessions were selected to measure the HR values of all participants, regardless of the level of CrossFit® experience. To describe the cardiovascular demands and the internal training load during the progression of the 1-h training sessions, the observation period was divided into different parts: warm-up (WU-part), power and skill training (A-part), and the WOD performance (B-part). As a result, this study investigated for the first-time HR values and quantified the internal training load of a 1-h CrossFit® training session in a local affiliated training center under practical settings. Performing CrossFit® in 1-h sessions divided into separate training parts requires different cardiovascular demands, resulting in significant differences in HR values during each part. Further, no significant difference in acute physiological demands and internal training load was observed between beginning and experienced CrossFit® athletes, see **chapter 6**.

STUDY III

Meier, N., Rabel, S., & Schmidt, A. (2021). **Determination of a CrossFit® Benchmark Performance Profile**. Sports, 9(6), 80.

https://doi.org/10.3390/sports9060080

Research Artikel

First Online. 2 June 2021

Due to contradictory data in scientific literature, on how parameters athletes focus on during training and competition preparation, more normative data on performance values and performance predictors are required. Since there is only one study with normative values for five common Benchmark workouts in the scientific literature so far (140), it remains open, how the performance profile is characterized in the common power lifts, Olympic lifts, and running performances across American and German CrossFit® athletes and what differences there are between the nations. Furthermore, the aim of this study is to determine what parameters or whether regional differences affect CrossFit® performance. For this reason, data were collected by questionnaire from athletes from the United States and Germany (n = 162) to provide a global performance profile of CrossFit® athletes and to assess performance predictors. The conceptual design of the study included first the preparation and validation of the questionnaire in both German and English language, and subsequently the collection of data in local CrossFit® affiliates and *via* online distribution of the survey. To date, no studies previously examined the Benchmark profiles from American and German CrossFit® athletes, so the obtained data characterized the performance profiles for the first time. To further interpret the results, the values were compared with a data set of millions online available data using the online benchmarking tool BTWB (51). As a result, the data set may be useful for standard inclusion and exclusion criteria for future research. In addition, the statistical analysis of the data provides significant indications of the evaluation of athletes' CrossFit® performance. Thus, the results are consistent with previous data in suggesting that squat performance is of major importance (126, 133). In summary, the study is useful for establishing an international performance ranking, identifying deficits, and assessing specific performance predictors, see **chapter 7**.

STUDY IV

Meier, N., Nägler, T., Wald, R., & Schmidt, A. (2022). **Purchasing behavior and use of digital sports offers by CrossFit® and weightlifting athletes during the first SARS-CoV-2 lockdown in Germany**. BMC Sports Science, Medicine and Rehabilitation, 14(1), 1-12.

https://doi.org/10.1186/s13102-022-00436-y

Research Artikel

First Online. 23 March 2022

Given actual circumstances, one research approach that incorporates this thesis addresses the consequences of the COVID-19 pandemic (143). With the initial spread of the SARS-CoV-19 virus in 2020 in Europe, several governments implemented preventive measures to combat the spread of the virus (147, 148). Because, for the first time in the short history of the sport of CrossFit®, widespread restrictions have affected the practice of the training, no scientific data were available on this issue at the start of the pandemic. Considering that the closure of CrossFit® training centers and gyms in Germany also posed a major challenge to any athlete (154, 155), regardless of their training content, the question remains as to how the closures affect the training behavior of CrossFit® athletes. Since, due to the nationwide lockdown from mid-March 2020 (164), no study of a control group maintaining training habits in affiliated training centers to be carried out, the methodological approach was indeed to compare the training behavior of CrossFit® athletes with a similar sport type, weightlifting. The aim of this study is therefore to investigate how the closure of training centers and gyms affects the training behavior of CrossFit® and weightlifting athletes, and what differences emerge between the disciplines. In detail, the research focuses on the use of digital sports offers, training habits, body weight changes, and the purchase of sports equipment between CrossFit® and weightlifting athletes during the first nationwide lockdown in Germany. After the preparation and validation of a questionnaire, the data collection (n = 484) was distributed and conducted solely in Germany and *via* an online survey, due to national differences in COVID-19 pandemic-related restrictions. The obtained data show for the first time, that both CrossFit® and weightlifting athletes purchase new equipment for training at home and the use of digital sport offers increased across all age groups. In addition, special differences between the sports disciplines were observed, providing detailed insights into the characteristics of CrossFit® athletes and how they habit during challenging times, see **chapter 8**.

5 Blood Lactate Concentration after a Short CrossFit® Workout

Full Title:

Delayed Increase in Blood Lactate Concentration after a Short, Intense CrossFit® Workout

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Research Article

Delayed Increase in Blood Lactate Concentration after a Short, Intense CrossFit® Workout

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Abstract

CrossFit®, the most successful concept for high-intensity interval training (HIIT), consists of constantly varied training loads und and is usually performed as Workouts Of the Day (WOD) with a length of 6 minutes and more. However, regular CrossFit® training concepts also include shorter WODs, the physiology responses have rarely been investigated yet. In this Study we wanted to analyze the blood lactate concentration (LAC) after ultra-short, high-intensive CrossFit® workout and investigate whether the kinetics of LAC is related to heart rate (HR) or the ratings of perceived exertion measured by borg-scale (borg-RPE). To determine whether CrossFit® workouts induces increased LAC levels after the exercise load, ten participants (n= 10; 8 males; 2 females) volunteered in the study. The participants completed a WOD consisting of 30/20 Calories AirBike and ten repetitions Devil Press with 10 kg/5 kg dumbbell (men/female). LAC, HR, and borg-RPE were measured immediately after, until 12 min after the WOD. The lactate turning points (LTP1 /LTP2) were previously determined using a bicycle ergometer performance diagnostic. The LAC values increased immediately after the WOD by 2.3 ± 1.4 fold (mean ± SD) of the LTP2 up to the maximum by 3.9 ± 0.96- fold during the post-workout observation period.

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Our results shows that a CrossFit® WOD induced delayed increased LAC levels, but this effect is not associated with borg-RPE. So the first time a time-delayed increase of LAC up to 4 times of LTP2 was observed after ultra-short, high-intensive CrossFit® workout as before only reported from short sprints.

Keywords: CrossFit® workout; Sport performance; Blood lactate; High-intensity interval training; Training load; Physical fitness

1. Introduction

The assumption that lactate (LAC) accumulates as a toxic waste product of the anaerobic metabolism due to an oxygen debt is omnipresent so that LAC is considered a fatigue agent throughout the first half of the last century [1]. However, the current state of research shows that LAC is much more than a waste product and performs various functions in the organism [2-7]. The ideas of the "cell-cell shuttle-theory" and the "intracellular lactate shuttle-theory" describe the functions of LAC as a gluconeogenic precursor [6]. LAC is a high-energy intermediate used in the anaerobic glycolysis for short-term high-energy turnovers [8]. Following these results, LAC is a relevant energy carrier for oxidative energy production and a precursor for gluconeogenesis [9]. LAC is transported back and forth between different cells, tissues, and organs via LAC shuttle mechanisms, a differentiation now is established between the "cell-cell shuttle" and the "intracellular lactate shuttle" [8].

In contrast, LAC also acts as a signaling molecule like a "pseudo-hormone" regulating protein and gene expression [10]. However, unawareness of the role of LAC has been associated with many negative effects in amateur athletes in the past and remains today. Sports science also assumes that increased LAC levels in the muscles lead to lactic acidosis, though it is still well accepted [11, 12]. In the traditional theory, it is assumed that LAC -induced acidosis promotes muscular fatigue and that the increased concentration of H(+) consequently limits muscle function [9]. However, the postulated mechanisms have not yet been verified under physiological temperatures. Current research results show only a temporary correlation between LAC values and blood pH values [13, 14].

Nevertheless, there is no direct causal relationship, and LAC causes no acidosis [15, 16]. However, the following syndrome is known, which includes the symptoms of nausea, malaise, general fatigue as well as possible vomiting and occurs within a period of 10 minutes after the completed training. Therefore, it is essential that the athlete feels a perceived exertion continues high or even increases after the physical exercise are over. Scientifically, this effect has not yet been defined more clearly, so there are only far documented case reports. In several online articles of specific endurance training for American football with a weight prowler, this symptom is also described as "Prowler Flu" [17]. An increased LAC level is supposed as a causal agent [18]. Achauer also assumes that the LAC -induced decreasing blood pH value results in vomiting. A fact that is also known as load-induced lactic acidosis [11]. Lactic

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acidosis symptoms include nausea, vomiting, heavy breathing, and general weakness, which coincide with the described effects. However, the assumption that increased LAC levels through glycolysis are responsible for a decreased pH-value, as already mentioned, is meanwhile contradicted [16]. The new trend sport CrossFit® is particularly well suited to investigate the factors that induce the feeling of an ongoing load after the finished exercise. CrossFit®, as varied, high-intensity interval training (HIIT), includes exercises from the main elements of gymnastics, weightlifting exercises, and cardiovascular activities.

CrossFit® training is usually performed as the "Workout of the day" (WOD), with the focus on constantly varying functional movements [19]. In the training sessions, highly intensive exercises are performed quickly, repetitively, and with little or no recovery time between sets [20]. Especially with short and high-intensity WOD (e.g., FRAN), many CrossFit® athletes report the symptoms described above after the training [21]. Considering that the CrossFit® area is permanently working with high intensities, this effect seemed not to be noticed unless vomiting occurs. The CrossFit® community also described it with the expression "Meeting Pukie" [11]. For rating the severity of these effects, the borg scale is a suitable method. The original Borg scale was developed to measure the Ratio of Perceived Exertion (borg-RPE) as a metric for physical strength [22]. The constant load of CrossFit® in the high-intensity range is known to result in increased LAC values shown by Tibana, 2018 [21]. The increased LAC levels under physical exertion are also used in LAC -based performance diagnostics. Specific intensity ranges can be identified based on the lactate curve (LC) determined by performance diagnostics. Many approaches exist to this purpose, some of which are based on severely obsolete perspectives on the role of LAC in the human organism [23]. The systematic application of lactate shuttle-theory shows that the temporal LC course is three-phase. LC implies three specific phases of energy delivery and, consequently, two turning points, respectively, the first (LTP1) and the second (LTP2) lactate turning point [24-26].

However, scientific evidence on how increased LAC concentrations affect CrossFit effectiveness is still missing, despite CrossFit® being the most successful HIIT approach. The few studies available have all examined typical WODs with a length of 6 minutes and more, usually how they are commonly performed [21, 27]. However, because the CrossFit® training concept consists of constantly varied training loads, regular CrossFit® training also includes WODs of much shorter duration, that have not yet been analyzed scientifically. To better understand the success of CrossFit, we wanted to analyze LAC concentration after an ultra-short, intensive CrossFit® workout with an average duration of fewer than 2 minutes and observe whether increased RPE can be induced by these WODs. It is known from 400 m runners or rowers that LAC increases sharply after exercise, so we wanted to know if ultra-short, intensive CrossFit® workouts can also lead to similarly high LAC concentrations [28]?.

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2. Materials and Methods

2.1 Study design

To investigate the role of LAC on heightened RPE after completion of a CrossFit® workout, blood LAC, HR, and borg-RPE using borg scale were measured. To correlate the measured LAC concentration with the borg-RPE values, LPT1 and LTP2 were determined previously using an ergometer performance diagnostic.

2.2 Participants

Eight health men (25.9 ± 2 body mass index (BMI)) and two females (22.6; 22.8 BMI) with a minimum of 6-month CrossFit® training experience (24 ± 22 months) participated in the present study (23 ± 2.4 years). The CrossFit® workload varied between 2 and 6 training units per week (4 ± 2 units/week). The participants also performed other sports, including swimming, running, and soccer (3 ± 2 units/week). The inclusion criteria were as follows: No muscle, joint, or bone injuries, no diseases at the time of the study, no smoking, and signed the written informed consent document.

2.3 Experimental design

The subjects participated in two different investigations, with 3 to 14 days apart. To determine the LTP1/LTP2, the first approach involved performance diagnostics on a bicycle ergometer on measures of LAC and HR. In the second trial, the participants performed a CrossFit® workout, and subsequently, the LAC, the borg-RPE, and HR were measured up to 12 minutes after completion.

2.4 Performance diagnostics

All subjects performed an incremental exercise test using an electromagnetically braked cycle ergometer (Assault Fitness, California, U.S). The exercise intensity was increased in a stepwise manner, with an initial level of 25 W/15W and increments of 25 W/15 W added every 60 s until the intensity limit of each individual was reached (male/female). The intensity limit was reached by the participants unable to maintain a frequency of minimum 60 rpm and a maximum 80 rpm. From the hyperemized ear lobe, capillary blood samples were taken at rest, after the 3-min warm-up, at the end of each load step, and at the end of the ergometric test to determine LAC. HR was measured continuously over the entire period. LTP1/ LTP2 was calculated by means of linear regression breakpoint analysis, as shown previously [24, 29].

2.5 WOD

After a 3-minute warm-up on the AirBike (Assault Fitness, California, U.S.) with individual intensity, the participants complete the WOD shown in Figure 1.

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The WOD consisted of reaching as soon as possible 30/20 calories on the AirBike, followed by ten repetitions of the exercise Devil Press with one 10/5 kg dumbbell per hand (male/female). After warm-up, LAC levels from capillary blood samples and borg-RPE were determined at rest, after warm-up, immediately after and 1,3,5,7,9,11 min after completing the workout. The test protocol is also shown in Figure 1. In addition, the borg-RPE was measured every minute after the end of the training session, and the HR was measured continuously during the training session.

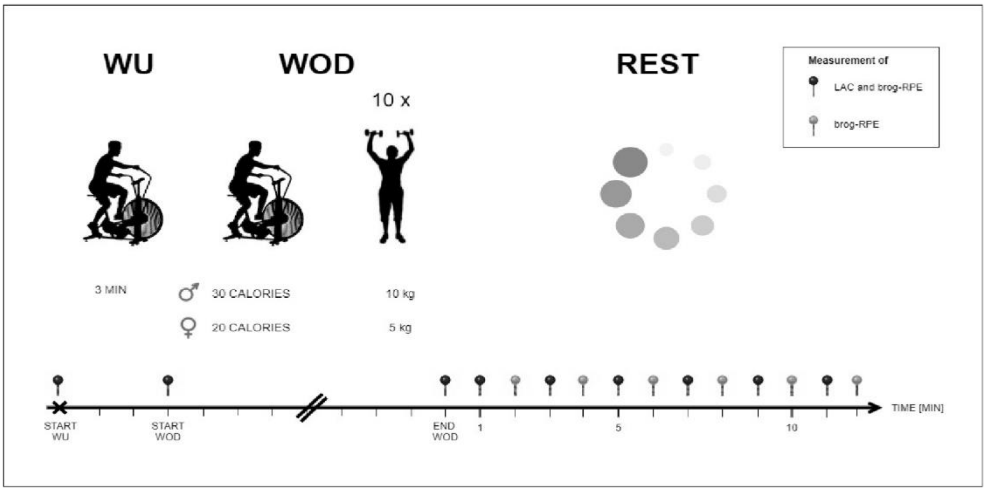

Figure 1: Performance of the CrossFit® Workout of the Day (WOD). Warm-Up (WU): 3 min AirBike at an individual intensity. WOD: as soon as possible reach 30/20 calories on the AirBike, followed by ten repetitions of the devil press with 10/5 kg dumbbell per hand (male/female). Test protocol of the time points blood lactate (LAC) and rate of perceived exertion by borg scale (borg-RPE) were measured after completing the WOD.

2.6 Blood lactate concentration (LAC)

To measure the LAC levels at the time points of testing protocol shown in Figure 1, capillary blood samples were taken from the ear lobe by using Gases and 70% alcohol for asepsis and a lancet to puncture the lateral pulp. A blood drop was inserted in the center of the test zone of the reactive tape by using the portable device "Lactate Scout+ "(SensLab GmbH, Leipzig, Germany).

2.7 Heart rate analysis (HR)

HR was measured continuously by using the "H7 heart rate sensor" (Polar Electro GmbH, Büttelborn, Deutschland) linked via Bluetooth with an Android smartphone. To collect the HR data, the app "HRV Elite" (Elite HRV Inc, Version 4.2.3, North Carolina, U.S.) and for analysis, the software "Kubios HRV" (Kubios Oy, Version 3.1 Kuopio, Finland) was used.

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2.8 Rating of perceived exertion by borg- scale (borg-RPE)

The Borg Scale was used to measure borg-RPE. The borg scale rated from 6 (no stress) to 20 (too heavy, no longer works) [22].

2.9 Statistical analysis

Data were presented as means with '±' for standard deviation (S.D.). IBM SPSS statistics version 26 (Somers, NY, USA) software was used for statistical analysis. Kolmogorov-Smirnov-Tests was applied to check for normal distribution of study variables. Correlations between the single measurements for LAC, borg-RPE, LAC/LTP2, and HR were assessed after Spearman. The Wilcoxon signed-rank test was used to compare samples. The 95% confidence intervals (95% CI) were calculated using bootstrapping.

3. Results

As part of the preparation, the individual lactate thresholds LTP1 and LTP2 were determined for each athlete using bicycle ergometry. The participants achieved LTP1 in mean at 139 W with a LAC concentration of 1.6 mmol/l and LTP2 at 250 W with LAC concentration of 3.7 mmol/l. Considered separately, the male participants achieved LTP1 at 156 W with a LAC concentration of 1.7 mmol/l and LTP2 at 273 W with LAC concentration of 3.9 mmol/l (Table 1).

On another day, the athletes completed the WOD, starting with a warm-up at the Assault-Bike. The WOD itself was a combination of 20/30 calories on the Assault bike and 10 Devil Press with 5/10 kg dumbbells (Figure 1). The average time for the WOD was 113 s. The athletes ended the warm-up with a mean heartrate (HR) of 126 bpm which increased up to a mean of 178 bpm after the WOD. 11 minutes later, the mean HR was still at 109 bpm. Direct after the WOD, participants indicated in mean a borg-RPE of 17.4, which corresponds to the state "You can no longer talk because your breathing is heavy". 11 minutes later, borg-RPE was down to 8.1. Before the warmup, the athletes had a mean LAC of 2.2 mmol/l, 95% CI [1.9, 2,7], which stayed with 2.0 mmol/l, 95% CI [1.4, 2.3], nearly unchanged after the warmup. Immediately after the WOD, the LAC increased significantly up to 8.4 mmol/l, 95% CI [4.47, 12.36], $Z(7) = 2.521$, $p = 0.012$, representing the 2.3-fold, 95% CI [1.18, 3.52] of the individual LTP2. Taking all points in time after the WOD into consideration, the maximum LAC was in the mean by 13.5 mmol/l, 95% CI [11.85, 15.85], $Z(9) = 2.80$, $p = 0.005$, which corresponds to 3.9, 95% CI [2.96, 4.77] times the LTP2 (Figure 2).

According to the Borg scale, the perceived strain was highest at the end of the WOD and then decreased continuously. It was the same with the HR. In contrast, LAC was lowest immediately after WOD and then increased continuously until 9 minutes afterward (Figure 3). The strongest correlation was found between borg-RPE and

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heartrate (r_s = .55, p<0.001). The correlation between borg-RPE and LAC was also significant (r_s = .27, p = 0.012) and got even better when the measured LAC concentrations were divided by the individual LTP2's (r_s = .34, p = 0.001). No correlations were found between HR and LAC concentrations (Table 2).

	Overall (n = 10)	**Males (n = 8)**	**Female 1**	**Female 2**
	Mean [95% CI]	**Mean [95% CI]**		
LTP1				
Watt (W)	139 [101, 176]	156 [120, 191]	72	72
LAC (mmol/L)	1.6 [1.28, 1.83]	1.7 [1.53, 1.90]	1.1	0.8
LTP2				
Watt (W)	250 [193, 307]	273 [213, 332]	140	176
LAC (mmol/L)	3.7 [2.88, 4.46]	3.9 [2.89, 4.84]	2.7	3.1
WOD time (sec)	113 [98, 127]	111 [92, 130]	105	131
0 min after WOD				
HR (bpm)	178 [167, 186]	177 [165, 188]	176	188
LAC (mmol/L)	8.8 [4.2, 13.4]	9.3 [3.8, 14.8]	5.7	12.4
LAC/LPT2 ratio	2.4 [1.0, 3.8]	2.5 [0.7, 4.2]	2.1	4.1
Borg-RPE	17.4 [16.3, 18.6]	17.3 [15.9, 18.8]	18	18
11 min after WOD				
HR (bpm)	109 [101, 116]	106 [99, 118]	110	127
LAC (mmol/L)	12.1 [9.8, 14.6]	12.7 [10.3, 15.2]	8.8	11.5
LAC/LPT2 ratio	3.5 [2.4, 4.1]	3.3 [2.2, 4.4]	3.2	3.8
Borg-RPE	8.1 [6.1, 10.2]	8.3 [5.9, 10.8]	7	7

Lactate Turning Points (LTP) of performance diagnostics are shown by means and SDs overall and by gender. Furthermore the table contains the values of the Heart rate (HR), Lactate-Concentration (LAC), and ratings of perceived exertion measured by borg-scale (borg-RPE) at the time of 0 min after completing the Workout of the Day (WOD) and 11 min after that.

Table 1: Lactate Turning points of performance diagnostics and physiological response after the CrossFit® workout given as means and 95% confidence interval (CI).

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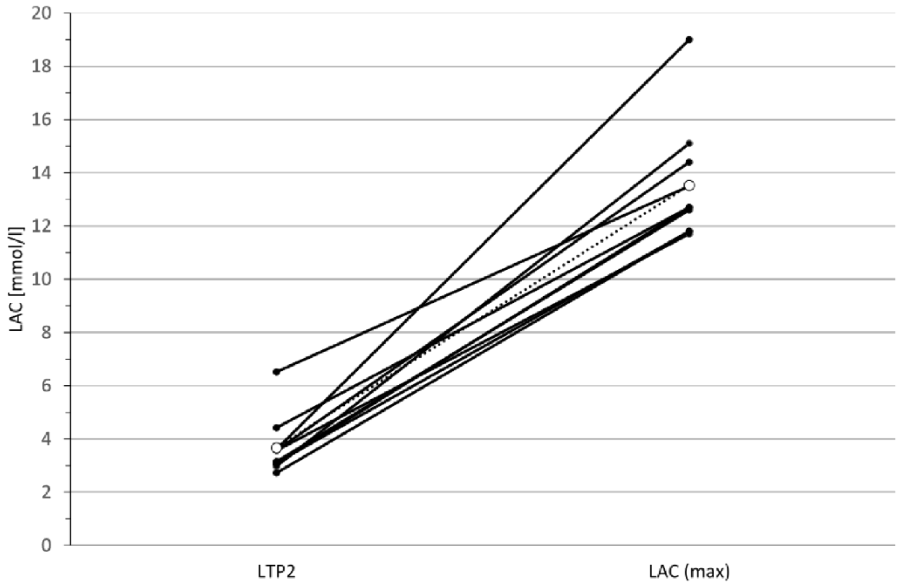

Figure 2: Comparison between the individual LPT2 and the maximum Lactate concentration 11 min after the WOD. Mean value is shown with the dotted line and the unfilled circles.

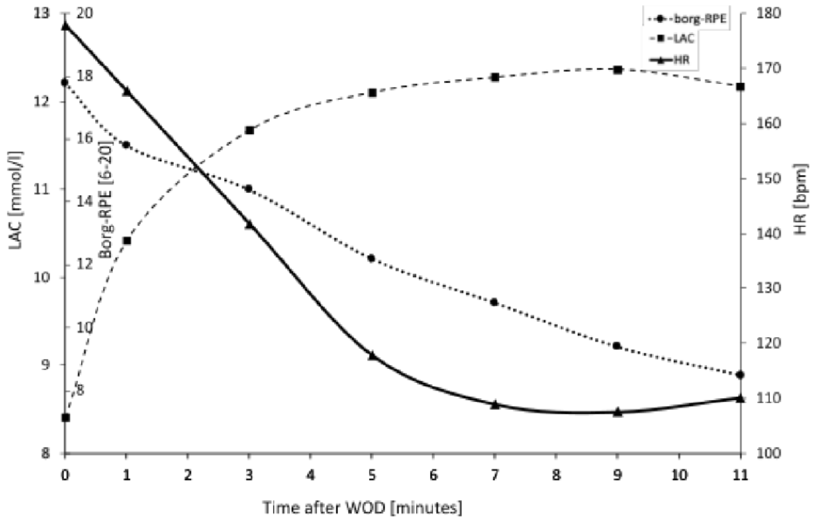

Figure 3: Means of Heart rate (HR), Lactate levels (LAC) and rate of perceived exertion by borg scale (borg-RPE) during 12 min after CrossFit® workout. After completion of the Workout of the Day (WOD) Borg-RPE and HR values decreased on average and LAC values increased.

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	HR		**LAC**		**LAC/LTP2**	
	r_s (95% CI)	**p**	**r_s (95% CI)**	**p**	**r_s (95% CI)**	**p**
borg-RPE	0.55 (0.31-0.70)	<0.001	0.27 (0.03-0.46)	0.012	0.34 (0.13-0,52)	0.001
LAC/LPT2	-0.17 (-0.38-0.05)	0.121	-	-	-	-
LAC	-0.2 (-0.39-0.01)	0.066	-	-	-	-

Table 2: Spearman correlation of heartrate (HR), borg-RPE, lactate (LAC) and the ratio of LAC and LTP2 (LAC/LPT2). Correlation between heartrate (HR), borg-RPE, lactate (LAC) and the ratio of LAC and LTP2 (LAC/LPT2) are analyzed by Spearman (r_s). The 95% confidence interval (CI) and the p-value are demonstrated.

4. Discussion

The examined WOD belongs to the ultra-short CrossFit workouts with an average duration of fewer than 2 minutes. Until now, only WOD's with a length of 6 minutes and more were analyzed. It is known that these WODs lead to the highest LAC concentrations immediately after ending the WOD [1, 21]. Our results demonstrated for the first time that ultra-short, high-intense workouts can have delayed aftermath on LAC. Whereas LAC was at 8.4 mmol/l direct after ending the WOD, and it increased by 61% in the following minutes up to 13.5 mmol/l. Such a time-delayed effect is described, for example, for short sprints [28], but not for HIIT like CrossFit WODs. LAC concentration does not go inline with the HR after the WOD. For HR, the highest was measured immediately after ending the WOD and reduced by 12 bpm per minute for the next 7 minutes, where it finally levels off. The same happened for the perceived physical strain, measured according to Borg. Also, here, the highest exertion was reported immediately after ending the WOD. But unlike HR, a plateau initially formed at borg-RPE, which is probably also the reason why there was at least a weak correlation between LAC and borg-RPE. However, as the distance from the WOD increased, the participants also felt increasingly better. On the other hand, there was a strong correlation between borg-RPE and HR. This positive correlation between HR and borg-RPE is in accordance with previous research results, which partly justify the Borg scale [30]. To the best of our knowledge, this is the first study to investigate the effects of LAC Levels on borg-RPE after CrossFit® training. Previous studies have reported these single parameters, but only during the CF workout or separately, and in response to different training models [27, 31, 32].

In our study, LAC values with 13.5 mmol/l were far above LTP2. Such high levels beyond LTP2 are known for HIIT workouts. HIIT that evokes high levels of lactic acid production in the working muscle hormonally triggers specific responses and may elicit certain benefits, such as improving LAC tolerance, and is also a reason for considerable improvements in VO2max [33]. In summary, we demonstrated for the first time that also HIIT workouts can lead to the same effect as short sprints. After only two minutes of load, the LAC concentrations had reached the double-fold of LTP2, didn't reached its maximum, and instead went up to four-fold in the minutes after ending the WOD.

Acknowledgements

None

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6 1-h CrossFit® Training Sessions: Cardiovascular Parameters

Full title:

Comparison of Cardiovascular Parameters and Internal Training Load of Different 1-h Training Sessions in Non-elite CrossFit® Athletes

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ORIGINAL ARTICLE

Comparison of Cardiovascular Parameters and Internal Training Load of Different 1-h Training Sessions in Non-elite CrossFit® Athletes

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Abstract

Purpose The fact that CrossFit® is the best-known and rapidly growing concept for high-intensity interval training (HIIT) and high-intensity functional training (HIFT) results in a continuous increase of athletes performing CrossFit®. In the more than 15,000 CrossFit® Affiliates worldwide, the training concept is usually offered in 1-h training sessions containing the CrossFit®-related workout of the day (WOD), as well as a general warm-up, movement demonstrations, and skill training. Here, we report how physiological parameters measured by heart rate (HR) values vary during four different 1-h CrossFit® training sessions of non-elite athletes ($n=27$) in a local affiliated training center and what influencing factors may exist.

Methods The duration of the 1-h training sessions were divided into a warm-up part (WU-part), a skill development part combined with strength exercises (A-part), followed by the WOD part (B-part).

Results Analysis of HR values shows high training intensity ($\geq 91\%$ HR_{max}) not throughout the duration of each training session, only during B-part. The mean HR values in B-part differ significantly compared to the remaining training parts ($P<0.001$) for all four training sessions. Comparison of different CrossFit® experience levels revealed no significant difference in acute physiological demands and training load between beginner and experienced CrossFit® athletes.

Conclusion Our results may suggest that practicing CrossFit® in 1-h training sessions combined anaerobic and aerobic exercise intensities, with the training concept allows beginners and experienced athletes to be trained with the same cardiovascular responses and training intensities.

Keywords CrossFit® performance · Training load · Exercise intensity · Cardiovascular response · High-intensity functional training

Introduction

The new training concept CrossFit® belongs to the most growing and popular types of high-intensity interval training (HIIT) and high-intensity functional training (HIFT) that counts over 15,000 affiliates training centers worldwide (CrossFit). Due to its increasing popularity and the multiple fitness improvements of CrossFit® training [4, 6], recent studies have investigated the physiological and cardiovascular responses [25–27].

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CrossFit® focuses on constantly varied functional movements executed at a high intensity and includes exercises from the main elements of gymnastics (e.g., Pull-Ups, Push-Ups, and Burpees), weightlifting (Power lifts, e.g., Back Squats, Deadlifts, and Olympic lifts, e.g., Snatch, Clean & Jerk) and cardiovascular activities (e.g., running, rowing, and jumping) usually performed as "workout of the day" (WOD) [17]. In affiliated training centers, CrossFit® training is commonly performed in 1-h classes consist of a warm-up part (WU-part), a part of skill development, possibly combined with strength exercises (A-part), followed by a 10–20-min part involving the WOD at a high intensity (B-part) with short or no intervals between exercises and as required, stretching exercises [18]. Greg Glassman's CrossFit® training principle assumes that all three energy systems (the phosphagenic pathway, the glycolytic pathway, and the oxidative pathway) are targeted during training, controlled by duration, intensity, and programmed exercises to improve

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performance. CrossFit® determines fitness as a result of training and improvements in each of these energy-delivery systems [16]. The combination of aerobic, anaerobic, and resistance training within each training session presents CrossFit® as an extremely effective training method for inducing improvements in cardiovascular fitness and body composition in athletes of all levels of fitness [15, 26, 31], in accordance with the key idea of CrossFit®, which is accessible to everyone by scaling CrossFit® workouts [19]. Scaling means the ability to adjust the intensity of each exercise of the workout to the individual fitness level as shown by Butcher et al. [3]. To better understand the effectiveness of CrossFit® training [4], the previous studies have examined cardiovascular and metabolic responses, as well as ratings of perceived exertion (RPE) of CrossFit® training protocols with varied durations ranging from ultra-short protocols of less than 2 min [28], to shorter protocols of only a few minutes (2–8 min) [13, 27, 35, 37, 38], and to longer protocols (20–30 min) [3, 12, 25, 41]. Tibana et al. examined the differences between shorter and longer CrossFit® sessions, and showed that both protocols achieved heart rate (HR) values over 90% maximal heart rate (HR_{max}) during training, with no significant differences [35]. In addition, differences between different CrossFit® training modalities such as "as many rounds as possible" (AMRAP) vs. "for time" (FT) have been investigated and show no differences in cardiovascular responses [13, 41].

According to the American College of Sports Medicine (ACSM) guidelines, previous studies reported that mean HR values during the CrossFit® workouts can be considered vigorous and close to maximal (~90% HR_{max}) overall [14]. However, only isolated WODs have been investigated as CrossFit® training routines, and no study has investigated a 1-h CrossFit® training session as commonly offered commercially by affiliated CrossFit® training centers [18]. Due to the intensity of the training, the used workload of CrossFit® WODs can be too excessive for some individuals, and a few studies reported increased acute cardiovascular stress [42], increased pro-/anti-inflammatory cytokines [34], injuries [11, 35], and rhabdomyolysis [20]. However, there is a lack of evidence of CrossFit® training as a risk of overtraining. Observational studies [11, 24, 32] suggest a comparable risk of injury to other sports and suggest that practicing CrossFit® in affiliated training centers incorporates more than the typically investigated WOD. To achieve positive physiological adaptations such as performance enhancement without the risk of overtraining and injury, it is essential to adopt an appropriate training load (TL). One of the major challenges in CrossFit® science is the quantification of internal TL, due to the wide variety of exercises used, external TL (e.g., speed, pace, distance, and repetitions) is a poor tool for monitoring. Few previous studies investigated the assessment of internal TL of CrossFit® training, e.g., during 38 weeks of CrossFit® training for an elite female athlete in a case study [36] and validated by session RPE method to quantify internal TL during HIFT [8, 10, 35, 36]. Although the variation of TL in different types of CrossFit® training "AMRAP" vs. "FT" has been recently shown by Toledo et al. [41], however to the best of our knowledge, it is not yet known how the TL varies in non-elite athletes between 1-h CrossFit® training sessions. To date, a few available studies have only examined the effect of separate CrossFit® WODs on physiological responses such as HR values [3, 12, 13, 25, 27, 35] but not the effect of CrossFit® practicing in 1-h training sessions, which maintain the WOD but incorporate even more. Understanding the physiological responses to different structures of CrossFit® training may help athletes to improve their training requirements and thus improve their results [4]. We suggest that a better understanding of how CrossFit® is performed in real training conditions like in 1-h training sessions by athletes of different levels of CrossFit® experience and its effects allows reducing the risk of injury and optimizing athletic performance. For this reason, we intend to examine whether a 1-h CrossFit® training session targets three energy-delivery systems and what cardiovascular responses are induced in each part of the training. We suppose that only in the B-part including the WOD of a 1-h training session, HR values above 90% HR_{max} will be observed, as described by the previous studies, while the other parts of the training session differ significantly in their exercise intensity. Furthermore, the acute effects of a 1-h CrossFit® training session on different levels of experience have not yet been investigated. Butcher et al. revealed that performing CrossFit® in high-intensity continuous (circuit) or HIIT modalities by advanced participants achieved higher mean HR values than the beginner group [3]; however, he did not investigate the HR throughout a 1-h training session. We therefore asked whether there are differences in the cardiovascular response of different levels of experience and whether a 1-h training session format is suitable for achieving multiple physiological and performance adaptations in beginners and experienced athletes by aerobic, anaerobic, and resistance training. We hypothesize that training programming with the CrossFit® concept is suitable for both beginners and experienced athletes to be trained in the same 1-h training session regardless of their levels of experience.

To characterize the cardiovascular response, as measured by HR values, during 1-h CrossFit® training sessions, we observed four training sessions from a local affiliated training center and analyzed the training intensity in different training parts of the training session. Furthermore, we compared the acute physiological demands of beginner and experienced none-elite CrossFit® athletes to determine if different CrossFit® experience levels impact.

Materials and Methods

Participants

In this study, 27 CrossFit® Athletes (male = 18; female = 9) participated, with an average age of 30.9 ± 4.2 years. The Athletes had a CrossFit® experience of 16.1 ± 13.3 months with a training scope per week of 2.9 ± 0.9 h; as in Table 1. All participants attended the 1-h training sessions offered at a local affiliated training center of CrossFit® and signed an informed consent form prior to participation. To investigate real training conditions, participants were not selected according to any other inclusion criteria such as minimum CrossFit® experience. The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Institutional Ethics Committee of the University of the Bundeswehr Munich, Germany.

Experimental Approach

To characterize the cardiovascular response in different parts of 1-h CrossFit® training session, four regular training sessions of a local affiliated training center were observed within 1 week. At the beginning of each examination, participants signed the informed consent statement, and the anthropometric data of the participants were collected. HR measurement was performed to determine the cardiovascular response. The participants were fitted with an HR monitor to begin observation of each 1-h CrossFit® training session. On consecutive days, the 1-h CrossFit® training session, subsequently named Training Sessions 1–4, was conducted. Each training session was divided into three parts, the first part includes general warm-up and movement demonstrations (WU-part), followed by a part with lifting and skill training (A-part), and the last part containing the CrossFit®-related WOD (B-part). The programming of each training session is shown in Table 2. Participants performed the provided exercises as indicated or scaled depending on their performance capacity.

Furthermore, to compare the cardiovascular response and the internal TL between different levels of CrossFit® experience, the participants were classified by their previous knowledge of CrossFit® training as beginners with up to 6 months of CrossFit® experience (hereafter referred to as beginner) and as experienced CrossFit® athletes with over 6 months of experience (hereafter referred to as experienced) [3, 6]. Thereby, the ratio between females and males was comparable with 62.5% males and 37.5% females among beginner and 68.42% males and 31.58% females among experienced participants in two groups.

Measures

Heart Rate

Subjects were fitted with an HR monitor (Polar H-10 sensor, Büttelborn, GER) and the HR was measured prior to starting the training session (HRpre), and during the training session. During each CrossFit® training session, HR averages were recorded every 2 s. HR data were stored and subsequently extracted into CVS files using the "Club-community in flow" app (Polar, Büttelborn, GER) and analyzed using Microsoft Excel spreadsheet program and SPSS version 26.0 (IBM, Armonk, NY, USA). The HR values were averaged for each training session in the three parts (WU-, A- and B-part), so that the average HR values of each training part were obtained (HR_{mean} WU, HR_{mean} A, and HR_{mean} B). In addition, the average heart rate was calculated over the entire duration of each training session (HR_{mean}). To compare HR data, HR_{max} was calculated for each participant using the equation $208 - 0.7 \times \text{age}$ [33]. Once the calculated HR_{max} was exceeded by the HR peak observed during the CrossFit® training sessions, the HR peak observed during the CrossFit® training session was used for HR_{max}. To compare the training intensity of the different training sessions, the percentages time of participants spent in the five intensity zones by Edwards (up to 60% HR_{max}; 60%–70% HR_{max}; 70%–80% HR_{max}; 80%–90% HR_{max}; and 90%–100% HR_{max}) during the training sessions were also calculated.

Table 1 Participant characteristics

Parameters	All	Beginner	Experienced	*P* value*
n	27	8	19	
Age (years)	30.9 ± 4.2	31.3 ± 3.7	30.7 ± 4.4	0.776
Height (cm)	179.1 ± 9.1	177.4 ± 9.4	179.8 ± 9.1	0.531
Weight (kg)	79.8 ± 11.9	77.5 ± 13.2	80.7 ± 11.5	0.529
Training scope per week (h)	2.9 ± 0.9	3.0 ± 0.9	2.9 ± 0.9	0.791
CrossFit® experience (months)	16.1 ± 13.3	4.9 ± 1.6	20.9 ± 13.2	0.002

The values are expressed as mean ± standard deviation (SD)

*Difference between groups of different level of CrossFit® experience

Table 2 Training program of Training Sessions 1–4 divided into three parts with respective durations

Training sessions	Training Session 1	Training Session 2	Training Session 3	Training Session 4
Time (min)	61	64	53	56
WU	Row Mobility	Burpees, Sit-Ups, Push-Ups, Air Squats and Lunges Mobility	Row Mobility	Row Mobility
Time (min)	18	28	20	22
A	Deadlift 4–4–4–4–4	Every 90 s for 15 min High Hang Snatch Overhead Squat	Every 90 s for 15 min 3 Power Clean (90% of 1-RM)	Strict Pull-Ups (weighted) 3×3–5
Time (min)	21	19	25	16
B	Team Lumberjack (in Teams of 2) 20 Deadlift 400 m Run 20 Kettlebell Swings 400 m Run 20 Overhead Squats 400 m Run 20 Burpees 400 m Run 20 Chest to Bar Pull-Ups 400 m Run 20 Box Jumps 400 m Run 20 Squat Cleans 400 m Run	AMRAP 18 Jumping Lunges 15 Sit-Ups 12 Hand Release Push-Ups 9 Box Jump overs, 60 cm for males, 50 cm for females	3 rounds for Time 21 Kettlebell Swings (Russian), 24 kg for males, 16 kg for females 15 Med Ball Cleans 9 Toes to Bar	"Fight Gone Bad" 3 rounds 1 min Wall Ball Shots, 9 kg for males, 7 kg for females 1 min Sumo Deadlift High Pull, 35 kg for males, 20 kg for females 1 min Box Jumps, 60 cm for males, 50 cm for females 1 min Push Press, 35 kg for males, 20 kg for females 1 min Row for Calories 1 min Rest
Time (min)	22	16	8	18

Each training session was divided into three parts: the first part was a warm-up (WU), followed by a lifting and skill part (A) and the last part including the workout of the day (B)

AMRAP as many rounds as possible, *RM* repetition maximum

Training Load

To compare the internal TL of the four 1-h CrossFit® training sessions, the HR-based method proposed by Edwards was used. This method integrates the total volume of the training session with the total intensity of the exercise session relative to five intensity zones. For each training session, the TL per hour was calculated by multiplying the accumulated duration in each HR zone with a multiplier allocated to each zone (up to 60% $HR_{max}=1$, 60%–70% $HR_{max}=2$, 70%–80% $HR_{max}=3$, 80%–90% $HR_{max}=4$, and 90%–100% $HR_{max}=5$) and then summated [9].

Statistical Analysis

All data are presented as mean ± standard deviation (SD), and descriptive statistics were performed on HR data and on participant characteristics; see Table 1. Data were tested for normality distribution by the Shapiro–Wilk test ($P<0.05$) and Q–Q plots and for homogeneity of the variance by Levene's test. Using boxplots, outliners were identified. To assess the effects of the different training sessions on HR values measured during each training part and on the TL, a one-way ANOVA was conducted with Bonferroni post hoc analysis to determine significant differences between the HR and TL values. For each training session, a repeated-measures ANOVA with a Greenhouse–Geisser correction was conducted to assess differences in HR in percentage of HR_{max} between the different training parts. The sphericity was confirmed through the Mauchly test and the effect size by eta squared. The Greenhouse–Geisser adjustment was used to correct for violations of sphericity. Furthermore, a two-way ANOVA was performed to analyze the effect of levels of CrossFit® experience and the four different training sessions on HR values and the TL. The level of statistical significance was $P<0.05$. Analyses were performed using the software package SPSS version 26.0 (IBM, Armonk, NY, USA).

Results

Analysis of Training Sessions 1–4

To characterize the cardiovascular response of four different 1-h CrossFit® training sessions by measuring the HR values and analyzing the training intensity in different training parts of the training session, the resulting HR values and the calculated TL of each training session are shown in Table 3.

We conducted a one-way ANOVA to assess the effects of different training sessions on HR measured during each training part and on the TL. Each training session was divided into the WU-part, A-part, and B-part; in these parts, the mean HR for each part was calculated. There were no outliers, according to inspection with a boxplot. Data were normally distributed for each group (Shapiro–Wilk test, $P > 0.05$ and Q–Q plots) and there was homogeneity of variance (Levene's test, $P > 0.05$). For HR data, the one-way ANOVA showed significant differences between training sessions for mean HR, for mean HRpre, for mean HR in WU-part and A-part in bpm, and in percentage of HR_{max}; as in Table 3. There was no statistically significant difference in mean HR in B-part for the different training sessions in bpm [F (3, 31) = 109.88, $P = 0.336$] and in percentage of HR_{max} [F (3, 31) = 26.62, $P = 0.310$]. The average TL per hour was highest in Training Session 2 (173.9 ± 19.2), and lower in Training Session 1 [− 22.4, 95%CI (− 53.1, 8.3)], Training Session 3 [− 28.6, 95%CI (− 62.3, 5.1)], and Training Session 4 [− 28.6, 95%CI (− 60.15, 2.9)]. No statistically significant difference was found for the TL between the different training sessions [F (3, 31) = 2.86, $P = 0.053$].

For Training Session 1, mean HR in percentage of HR_{max} was the highest in the B-part (85.25 ± 4.06), and lower in the A-part (61.76 ± 7.31), WU-part (54.68 ± 5.10), and PRE of the Training Session 1 (44.26 ± 5.52). To assess differences in HR values between the different training parts, repeated-measures ANOVA with a Greenhouse–Geisser correction determined that mean HR in percentage of HR_{max} showed a statistically significant difference between training parts of Session 1 [F (1.98, 17.79) = 173.70, $P < 0.001$,

Table 3 Comparison of heart rate (HR) values and training load (TL) between the four 1-h CrossFit® training sessions

Variables	Training Session 1 $n = 10$	Training Session 2 $n = 9$	Training Session 3 $n = 7$	Training Session 4 $n = 9$	P value
HR_{max}					
(beats/min)	187 ± 2.0	188 ± 6.0	188 ± 4.0	188 ± 3.9	0.967
HR_{pre}					
(beats/min)	83 ± 10.6	88 ± 10.3	85 ± 11.3	72 ± 6.6	0.011
(% HR_{max})	44.26 ± 5.52	46.75 ± 4.17	45.09 ± 5.85	38.44 ± 3.34	0.006
HR_{mean}					
(beats/min)	128 ± 8.9	139 ± 9.7	128 ± 14.4	126 ± 8.8	0.047
(% HR_{max})	68.23 ± 4.55	73.93 ± 3.20	68.14 ± 7.43	67.09 ± 4.26	0.025
HR_{peak}					
(beats/min)	182 ± 7.2	182 ± 11.8	178 ± 12.0	183 ± 6.3	0.729
(% HR_{max})	97.25 ± 3.84	96.67 ± 3.81	94.38 ± 6.18	97.30 ± 2.65	0.486
HR_{mean} WU					
(beats/min)	103 ± 9.9	128 ± 9.3	112 ± 13.1	103 ± 9.0	< 0.001
(% HR_{max})	54.68 ± 5.10	68.26 ± 3.63	59.29 ± 6.46	55.07 ± 4.29	< 0.001
HR_{mean} A					
(beats/min)	116 ± 14.2	131 ± 11.0	130 ± 16.5	110 ± 13.9	0.006
(% HR_{max})	61.76 ± 7.31	69.53 ± 3.80	68.96 ± 8.54	58.42 ± 7.18	0.004
HR_{mean} B					
(beats/min)	160 ± 7.6	168 ± 11.7	165 ± 12.1	166 ± 7.2	0.336
(% HR_{max})	85.25 ± 4.06	89.10 ± 4.31	87.74 ± 6.50	88.32 ± 3.76	0.310
TL					
(TL/h)	151.5 ± 20.7	173.9 ± 19.2	145.3 ± 37.1	145.3 ± 17.3	0.053

The values are expressed as mean ± standard deviation (SD)

HR heart rate, HR_{pre} heart rate previous training session starts, HR_{max} maximum heart rate, % percentage, HR_{peak} maximum heart rate during training session, *WU* warm up-part, *A* A-part, *B* B-part, *TL* training load, *h* hour partial $\eta^2 = 0.95$]. The Bonferroni-adjusted post hoc analysis revealed significant differences ($P < 0.001$) in mean HR in percentage of HR_{max} between all training parts of Training Session 1; as in Table 4. Mean HR in percentage of HR_{max} was significantly higher in the B-part (85.25 ± 4.06) of Training Session 1 than in the remaining parts, with a mean difference of 31.69 (SE = 2.03), Bonferroni-adjusted $P < 0.001$, partial $\eta^2 = 0.96$; see Fig. 1.

The repeated-measures ANOVA with a Greenhouse–Geisser correction showed a statistically significant difference between training parts of session 2 for mean HR in percentage of HR_{max} [F (2.02, 16.12) = 264.35, $P < 0.001$, partial $\eta^2 = 0.97$]. Although no significant difference was found between mean HR in the WU-part and the A-part, Bonferroni-adjusted post hoc analysis revealed significant differences ($P < 0.001$) in mean HR as a percentage of HR_{max} between each of the other training parts of session 2; as in Table 4. Overall, the mean HR in percentage of HR_{max} was significantly higher in the B-part (89.10 ± 4.31) of Training Session 2 than in the other training parts, with a mean difference of 27.58 (SE = 1.25), Bonferroni-adjusted $P < 0.001$, partial $\eta^2 = 0.98$.

Mean HR in percentage of HR_{max} showed a statistically significant difference between training parts of session 3 [F (1.51, 9.05) = 117.35, $P < 0.001$, partial $\eta^2 = 0.95$], determined by a repeated-measures ANOVA with a Greenhouse–Geisser correction. The Bonferroni-adjusted post hoc analysis revealed significant differences ($P < 0.001$) in mean HR as a percentage of HR_{max} between mean HR in B-part and A-part, between B-part and WU-part, and between B-part and PRE-part. Besides, significant differences ($P < 0.05$) were found between A-part and WU-part, A-part and PRE-part, and WU-part, and PRE-part; as in Table 4. With a mean difference of 29.96 (SE = 1.88), the mean HR in percentage of HR_{max} was significantly higher in the B-part (87.74 ± 2.45) of Training Session 3 than in the other training parts, Bonferroni-adjusted $P < 0.001$, partial $\eta^2 = 0.98$.

Also in Training Session 4, the repeated-measures ANOVA with a Greenhouse–Geisser correction showed a statistically significant difference between training parts for mean HR in percentage of HR_{max} [F (2.13, 14.94) = 237.34, $P < 0.001$, partial $\eta^2 = 0.97$]. The Bonferroni-adjusted post hoc analysis revealed significant differences ($P < 0.001$) in mean HR as a percentage of HR_{max} between all four training parts in session 4, between WU-part and PRE-part by $P < 0.05$; as in Table 4. The mean HR in percentage of HR_{max} was significantly higher in the B-part (88.29 ± 1.42) than in the other training parts of Training Session 4, with a mean difference of 38.12 (SE = 1.71), Bonferroni-adjusted $P < 0.001$, partial $\eta^2 = 0.99$.

Training Intensity

During all training sessions, HR values ≥ 91% of HR_{max} were achieved. Considering the entire duration of the training session, 41 min was required to achieve ≥ 91% of HR_{max} during Training Session 1, 49 min during Training Session 2, 46 min during Training Session 3, and 42 min during Training Session 4. If only considering the B-part, with the WOD, Training Session 3 attained ≥ 91% of HR_{max} the fastest with 63 s, followed by Training Session 2 with 104 s, Training Session 1 with 169 s, and Training Session 4 with 230 s. Likewise, when observing the overall training duration, HR values ≥ 91% of HR_{max} are shown to be the least proportion of training time and occur during B-part, as well. To analyze the training intensity of the different training sessions (supplementary Fig. 1) shows the percentage of time spent by participants in the different HR zones during the training sessions. Athletes spent in average 14.08% ± 8.71% of the training time at intensities ≥ 91% of HR_{max}, followed by 15.00% ± 6.50% of the training time at intensities

Table 4 Pairwise comparisons of the mean heart rate (HR) in percentage of the maximum heart rate (HR_{max}) for the training parts PRE, WU, A and B by Bonferroni-adjusted post hoc analysis

Comparisons	Training Session 1		Training Session 2		Training Session 3		Training Session 4	
	d (%)	95%-CI	d (%)	95%-CI	d (%)	95%-CI	d (%)	95%-CI
HR_{mean} B vs. HR_{mean} A	23.49**	16.22–30.77	19.56**	16.42–22.70	18.78**	13.01–24.55	30.32**	22.56–38.08
HR_{mean} B vs. HR_{mean} WU	30.58**	23.96–37.19	20.84**	15.92–25.75	28.45**	20.97–35.93	33.66**	26.94–40.38
HR_{mean} B vs. HR_{mean} PRE	40.99**	32.78–49.20	42.35**	35.30–49.40	42.65**	30.36–54.94	50.37**	42.93–57.82
HR_{mean} A vs. HR_{mean} WU	7.08**	3.13–11.03	1.28	− 3.31–5.86	9.68*	3.39–15.96	3.34**	− 2.05–8.73
HR_{mean} A vs. HR_{mean} PRE	17.50**	10.86–24.13	22.79**	17.72–27.85	23.87*	11.47–36.27	20.05**	11.03–29.08
HR_{mean} WU vs. HR_{mean} PRE	10.42**	6.83–14.00	21.51**	15.67–27.35	14.19*	6.74–21.64	16.71*	11.93–21.50

HR heart rate, HR_{pre} heart rate previous training session starts, % percentage, HR_{peak} maximum heart rate during training session, *WU* warm up-part, *A* A-part, *B* B-part, *d* difference, *CI* confidence interval

**$P < 0.001$; *$P < 0.05$

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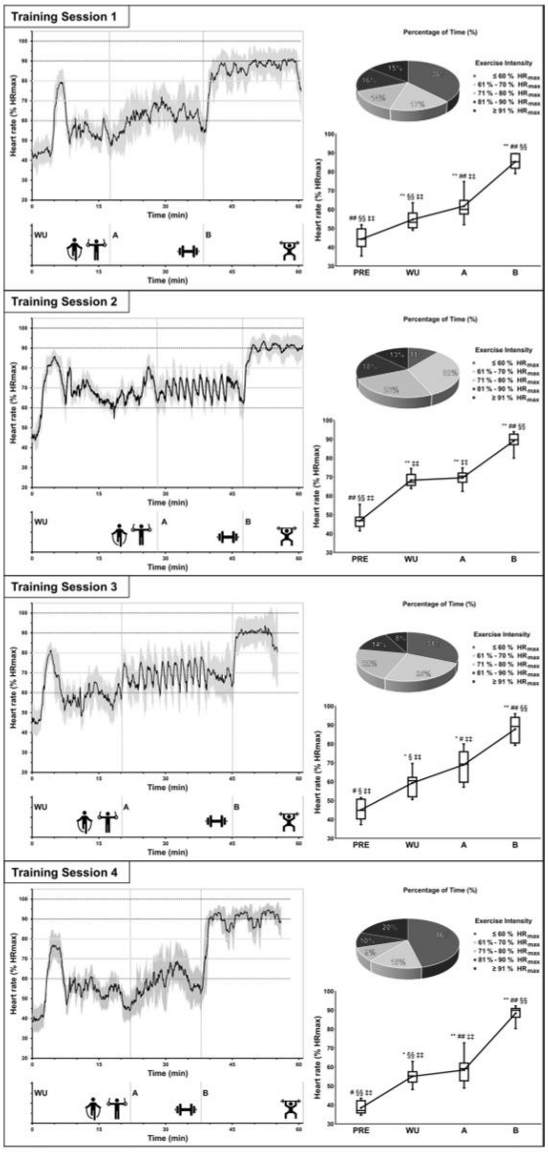

Fig. 1 Relative Heart rate (HR) values of HR_{max} during CrossFit® Training Sessions 1–4 with standard deviation of HR shown as shaded area. The duration of Training Session 1 in minutes is divided into three parts by gray dotted lines: Warm-up part (WU), followed by a lifting and skill part (**A**) and the last part with the workout of the day (**B**). The exercise intensity in the different HR zones is represented by colored dashed lines and shown separately in percentage of time (%) in the HR zones in a circular diagram. Differences in mean HR values between the different training parts: *Significant difference in relation to PRE ($P<0.05$); **Significant difference in relation to PRE ($P<0.001$); #Significant difference in relation to WU ($P<0.05$); ##Significant difference in relation to WU ($P<0.001$); §Significant difference in relation to A ($P<0.05$); §§Significant difference in relation to A ($P<0.001$); ‡‡Significant difference in relation to B ($P<0.001$)

81%–90% of HR_{max}, 17.50% ± 8.98% of the training time at intensities 71%–80% of HR_{max}, 22.04% ± 9.97% of the training time at intensities 61%–70% of HR_{max}, and the most of time the athletes spent in ≤ 60% of HR_{max} by 31.39% ± 18.42%.

Comparison of Different Levels of CrossFit® Experience

Furthermore, we asked whether different levels of CrossFit® experience affect the cardiovascular response as measured by HR values during the four 1-h training sessions. To examine the effect of levels of CrossFit® experience and the four different training sessions on HR values and TL, we performed a two-way ANOVA. The level of CrossFit® experience has been divided into beginner with up to 6 months of CrossFit® experience and experienced athletes with over 6 months [6]. There were no outliers, according to inspection with a boxplot. Data were normally distributed for each group (Shapiro–Wilk test, $P > 0.05$ and Q–Q plots) and there was homogeneity of variance (Levene's test, $P > 0.05$). A two-way ANOVA revealed that there was not a statistically significant interaction between the effects of levels of CrossFit® experience and the four 1-h training sessions. Simple main effects analysis shows that level of CrossFit® experience did not have statistically significant effects on any HR value or the TL, *P* values; as in Table 5.

For within-levels of CrossFit® experience comparisons of cardiovascular responses to each training session, significant differences were found for mean HR (in percentage of HR_{max}) in WU-part as well in beginner [F (3, 9) = 7.67, $P < 0.05$] as in experienced athletes [F (3, 21) = 8.65, $P < 0.001$] (Fig. 2).

Table 5 Comparison of heart rate (HR) values and training load (TL) in beginners and experienced CrossFit® athletes

Variables	Beginner ($n = 8$)	Experienced ($n = 19$)	*P* value
HR_{max}			
(beats/min)	189.25 ± 4.76	187.42 ± 3.67	0.261
HRpre			
(beats/min)	79.50 ± 11.46	82.92 ± 11.16	0.570
(%HR_{max})	42.00 ± 5.89	44.20 ± 5.44	0.417
HR_{mean}			
(beats/min)	128.43 ± 12.80	131.25 ± 10.70	0.691
(%HR_{max})	67.84 ± 6.15	70.00 ± 5.12	0.440
HR_{peak}			
(beats/min)	181.56 ± 8.42	181.46 ± 9.20	0.930
(%HR_{max})	95.73 ± 5.23	96.86 ± 3.66	0.523
HR_{mean} WU			
(beats/min)	108.35 ± 15.76[a]	112.42 ± 14.29[a]	0.589
(%HR_{max})	57.25 ± 7.47[a]	59.97 ± 7.30[b]	0.376
HR_{mean} A			
(beats/min)	116.81 ± 17.60	122.61 ± 15.62	0.503
(%HR_{max})	61.78 ± 9.11	65.37 ± 7.59	0.367
HR_{mean} B			
(beats/min)	164.49 ± 10.70	164.44 ± 9.76	0.969
(%HR_{max})	86.92 ± 5.30	87.77 ± 4.50	0.725
TL			
(TL/h)	147.8 ± 28.6	157.1 ± 24.4	0.497

The values are expressed as mean ± standard deviation (SD) and *P* value for variables between the levels of CrossFit® experience

HR heart rate, HR_{pre} heart rate previous training session starts, HR_{max} maximum heart rate, % percentage, HR_{peak} maximum heart rate during training session, *WU* warm up-part, *A* A-part, *B* B-part, *h* hour

[a]Difference between training session ($P < 0.05$)

[b]Difference between training session ($P < 0.001$)

Discussion

The results of this study demonstrate for the first time that practicing CrossFit® in 1-h training sessions, divided into different training parts, showed significantly different cardiovascular responses measured by HR values across the separate parts of the training sessions; however, by comparing athletes with different levels of CrossFit® experience, there were no significant differences of the cardiovascular responses. We therefore suggest that 1-h training sessions offered by affiliated training centers are likely suitable training methods to reach the recommended target exercise intensities for both beginners and experienced CrossFit® athletes.

Characterization of the cardiovascular demand of four 1-h duration of CrossFit® training sessions divided into different parts according to training scope, consisting of a warm-up part (WU-part), a skill development part, possibly combined with strength exercises (A-part), followed by the WOD part at high intensity (B-part) were the main findings of this study. The primary result shows that HR values (expressed as % of HR_{max}) above 90% HR_{max} are achieved in all four 1-h training sessions; however, in particular, these values were only observed in the B-part of the session, containing the WOD and differ significantly with 27.58%–38.12% more of HR values to the other parts. Our findings contrast with other studies by showing how the cardiovascular response varies throughout a 1-h training session. According to previous studies, it was assumed that CrossFit® training mainly performed in HR values above 90% HR_{max} [3, 12, 13, 25, 27, 41]. Furthermore, the comparison of the HR values between the four training sessions shows that the average values differ in the WU-part and the A-part; only in the B-part, no significant differences were found across the training sessions. This is an interesting finding, on one hand, the different HR values in the WU-part and A-part could be explained by the

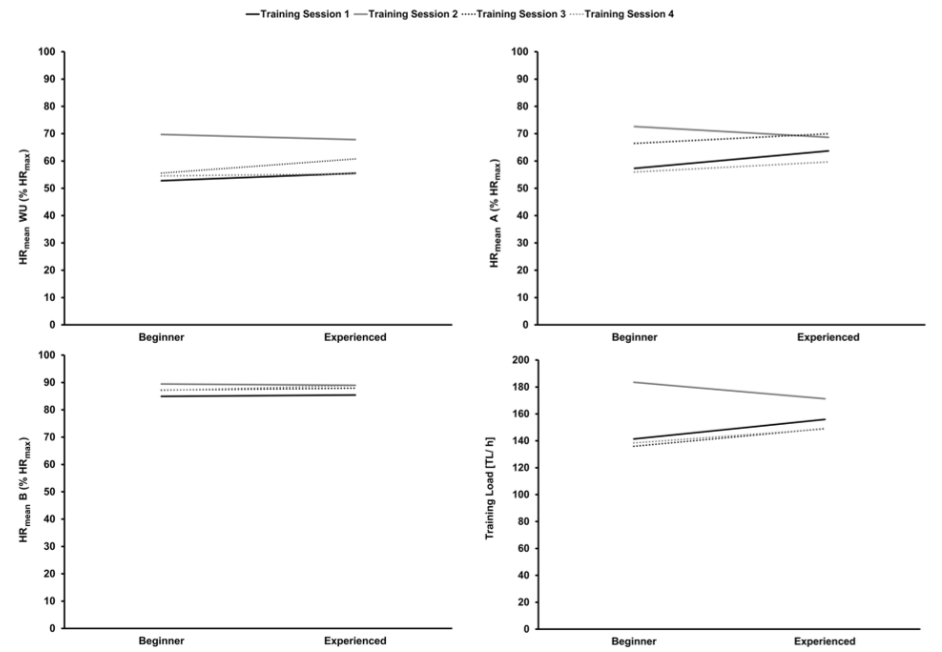

Fig. 2 Difference in Heart rate (HR) values for mean HR in WU-part, A-part, and B-part in % of HR_{max} and Training load (TL) between beginner and experienced CrossFit® athletes

different training programming, on the other hand, different WOD training modalities in the B-part do not lead to significant differences between the training sessions.

To the best of our knowledge, no previous study has examined the cardiovascular responses of a 1-h CrossFit® training session commonly offered at affiliated training centers. To date, several studies have only been able to show that HR values do not differ between different CrossFit® workouts when the WOD was investigated [13, 41]. Therefore, as the WOD is performed in the B-part in our approach, the results are consistent with the findings of previous studies regarding the HR values (expressed as % of HR_{max}) during WODs [12, 27, 35]. Thereby, in our study, different training modalities of the WOD were examined during each B-part. In Training Session 1, the WOD "in Team of 2", in Training Session 2 the training modality "ARAMP", in Training Session 3 the modality "FT" and in Training Session 4 the benchmark WOD "Fight Gone Bad" were performed, despite the different WOD types, the mean HR values did not differ significantly across the modalities. Thus, we suggest that all four different WODs are suitable for achieving HR values above 90% HR_{max}, as showed in some former studies [35, 41].

The present study explains the significant difference in the cardiovascular response of the other parts of the training session (WU- and A-Part) investigated with the fact that, for the first time, a 1-h training session was observed and not just a WOD alone. On average, high HR values above 90% HR_{max} were only reached after three-quarters of the training time and not after a few seconds, as Tibana et al. previously postulated [35]. Therefore, observing the entire duration of the training sessions contributes significantly to the evaluation of the cardiovascular response and allows us to better understand the training concept of CrossFit®. The previous assumption that CrossFit® mainly performed at vigorous training intensities was challenged by the present study. Nevertheless, CrossFit® workouts are known for being performed with high effort [4]. However, when CrossFit® is practiced in 1-h training sessions, the assumption that this high level of effort must be maintained throughout the entire duration of the session is misleading. Rather, our results suggest that the CrossFit® training concept provides for a progressive cardiovascular load increase during 1-h training sessions, with the maximum HR values, as typical for high-intensity training [40], being achieved only during the WOD in the last part (B-part) of the training session. We were able to show for the first time that the training concept of CrossFit® by practicing in 1-h training sessions may enable a combination of aerobic, anaerobic, and resistance training within each training session. On average, only the smallest amount of training time of a 1-h training session, concretely 14.08% ± 8.71% of training times, occurs at intensities ≥ 91% of HR_{max}, followed by training times at intensities of 81%–90%, of 71%–80%, and of 61%–70% of HR_{max}, in order. A surprising result was that the most of time of a 1-h training session the athletes spent was in Zones with ≤ 60% of HR_{max}. Therefore, we concluded that it is reasonable for the assumption of practicing CrossFit® in a 1-h training session based on the training guide utilizes all three energy systems [18].

The US Department of Health and Human Services, in its Physical Activity Guidelines for Americans (PAGA), requires at least 150 to 300 min per week of moderate aerobic activity or at least 75 min per week of vigorous aerobic activity for adults and also muscle-strengthening activity at least 2 days each week, to obtain health benefits [29]. Our results show that with 2–3 1-h CrossFit® training sessions per week, PAGA recommendations for significant health benefits are achieved. Higher exercise intensities, as shown in this study, result in greater health benefits [14]. Therefore, other studies demonstrated that HIFT is also useful to improve health-related fitness in inactive or overweight adults [2, 11]. Furthermore, since our results showed no significant differences in cardiovascular responses between beginner and experienced CrossFit® athletes, we suggest that CrossFit® performed in a 1-h training session may provide health and fitness benefits for any athlete, regardless of experience. Since already proven that HIIT can induce improvements in cardio-metabolic disease risk factors [1, 22, 23], based on our findings, future research might investigate the benefits of performing scaled CrossFit® in 1-h training sessions for various health aspects. To achieve positive physiological adaptations without the risk of overtraining and injury, one major challenge in CrossFit® science is the quantification of internal TL. Characterization of the TL is also necessary to analyze the periodization of training. Our study observed the variation of internal TL of 1-h training sessions of a local affiliated training center within 1 week; however, the observed period is too short to predict any evidence about the periodization of the training. However, despite the different training modalities in part-B, the results show that there are no significant differences in internal TL between the investigated 1-h CrossFit® training sessions. Adequate periodization of the internal TL during the training week is important to assure that an appropriate physiological stimulus is provided while ensuring sufficient time for recovery [30]. Based on our results, future studies may analyze the internal TL over a longer period to make recommendations for the periodization of CrossFit® training in 1-h durations.

Despite the novel findings, the study is not without limitations. The limitation of the present study is the lack of RPE measurement as an indicator of the physiological response or to calculate the internal TL by session RPE [35, 36]. Quantifying the internal TL by Edward's method uses only standardized predefined zones in contrast to other methods that use the HR zones based on individual parameters obtained in laboratory [21]. Another limitation is calculating the HR_{max} using an equation instead of experimental measurements, e.g., the Conconi test [5]. Therefore, further investigations should verify our findings by continuing the examination of 1-h CrossFit® training sessions over a longer period of time using experimental measurements of physiological response. Another limitation is the lack of load quantification as weight on the bar due to CrossFit® involving resistance training.

This study showed for the first time the cardiovascular responses and quantified the internal TL of 1-h CrossFit® training sessions. The results of this study demonstrate that practicing CrossFit® in 1-h training sessions, divided into separate parts, shows significantly different HR values during each part; however, heart rate did not differ in the last part (B-part) across the training sessions, which included the WOD. In addition, when comparing the different levels of CrossFit® experience, no differences in HR values and TL were found between beginners and experienced athletes. Our results suggest that CrossFit® training performed in 1-h training sessions is suitable for both beginner and experienced athletes regardless of their CrossFit® experience and may improve their cardiovascular fitness. In summary, our data provide a major contribution for a better understanding of practical training conditions during 1-h CrossFit® classes commonly offered at affiliated training centers.

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Author Contributions NM prepared the manuscript. NM and AS designed the methodology of the study and DS performed data collection. Investigation and statistical analysis were performed by NM. AS and NM edited the manuscript and AS provided administrative oversight. All authors read and approved the final manuscript before publication.

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Availability of Data and Materials The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of Interest The authors have no relevant financial or non-financial interests to disclose.

Ethics Approval and Consent to Participate The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Ethics Committee of University of the Bundeswehr Munich, Germany (06/04/2018).

Consent to Participate All participants sign the consent form and confirm their agreement with the use of their data before participation.

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This article is accompanied by the following supplementary information.

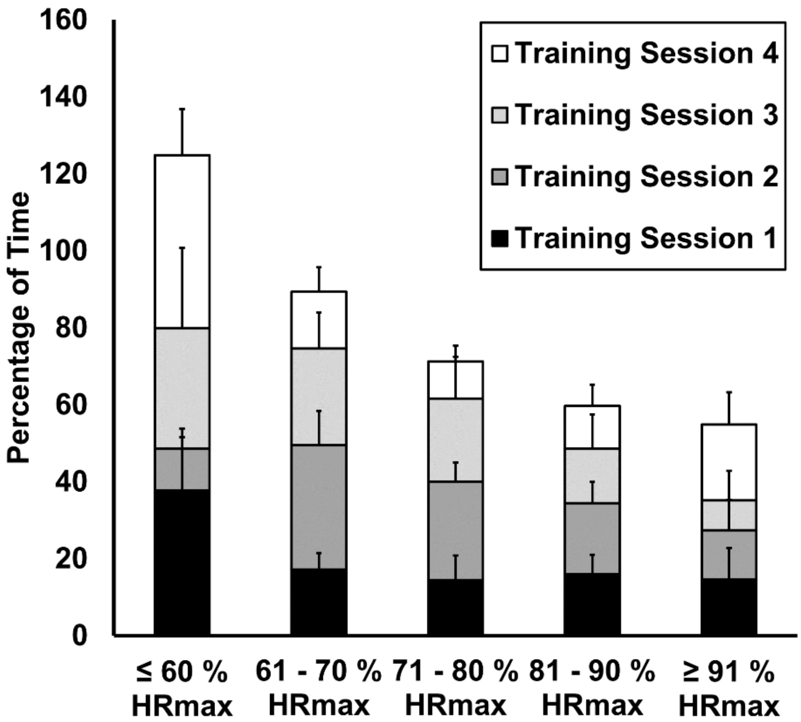

Figure 8. Supplementary file1 Fig. 1 Percentage of time spent by participants in the different heart rate (HR) zones during the training sessions from (167).

7 Determination of a CrossFit® Benchmark Performance Profile

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Determination of a CrossFit® Benchmark Performance Profile

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Abstract: In the trend sport CrossFit®, international competition is held at the CrossFit® Games, known worldwide as the definitive fitness test. Since American athletes are the best in the world regarding CrossFit®, there might be influencing factors on international competition performance. Here, we characterize the benchmark performance profile of American and German CrossFit® athletes (n = 162). To collect the common benchmark performance by questionnaire, 66 male and 96 female CrossFit® athletes (32.6 ± 8.2 years) participated in our survey in both nations. By comparing the individual performance variables, only a significant difference in total power lift performance by males was identified between the nations ($p = 0.034$). No other significant differences were found in the Olympic lift, running, or the "Girl" Workout of the Day (Fran, Grace, Helen) performance. Very large to extremely large (r = 0.79–0.99, $p < 0.01$) positive correlations were found between the power lift and Olympic lift variables. Further linear regression analysis predicted the influence of back squat performance on performance in the Olympic lifts, snatch ($R^2 = 0.76$) and clean and jerk ($R^2 = 0.84$). Our results suggested a dominant role of back squat performance in the assessment of physical fitness of CrossFit® athletes.

Keywords: benchmark performance profile; CrossFit® sport performance; high-intensity interval training; back squat performance

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1. Introduction

In the international competition of the trend sport CrossFit®, the CrossFit Games®, the athletes reach top performances every year [1]. Few previous studies have examined physiological variables that predict the performance at the CrossFit® Games [2]. Despite Martínez-Gómez et al. associating athletes' performances at the CrossFit® Games Open 2019 with various power, strength, and aerobic markers [3], so far there are still no specific criteria that allow a prediction of the performance.

The training modality of CrossFit®, as varied, high-intensity interval training (HIIT), includes exercises from the main elements of gymnastics, weightlifting exercises, and cardiovascular activities, and is usually performed as the "Workout of the Day" (WOD), with the focus on constantly varying functional movements [4]. The CrossFit® training concept aims to prepare athletes to perform a variety of workouts. Considering that the constant variation of workouts is an essential element of CrossFit®, in international competitions the WOD requirements are only announced to the athletes a few minutes before the competition [5]. The last-minute announcement of the WOD is an essential difference from other sports, as otherwise it is always known exactly which discipline will be performed in the next competition. Top performance in competition, as in any other sport, is only achievable after years of scheduled training, and requires continuous progression that is monitored in some manner during training [6].

Determining benchmarks and ascertaining performance variables of specific exercises and WODs can be applied for the progression monitoring [7]. Due to the constant variability of training, determination of benchmark performance is necessary, especially in CrossFit®. Since 2008, CrossFit® athletes can use the online software "Beyond the Whiteboard" (BTWB) to collect benchmarks performance data and compare them with others.

For this purpose, particular benchmark workouts have been developed in CrossFit®, like "Hero" WODs or "Girl" WODs. These benchmark workouts must be performed to the same specifications every time [8]. For the "Fran" WOD, there are three rounds, including 21, 15, and 9 repetitions, for time, of 95/ 65-pound barbell thrusters (male/ female) and pull-ups. The "Grace" WOD includes 30 repetitions of 135/ 95-pound clean and jerk (male/ female) for time, and the "Helen" WOD includes 3 rounds of a 400 m sprint, 21 repetitions of 53/ 35-pound American kettlebell swing, followed by 12 pull-ups. In parallel, CrossFit® also applies the performance variables in the most common weightlifting exercises for performance benchmarking. So, the one-repetition maximum (1-RM) of the power lifts (deadlift, back squat, bench press, and shoulder press) and the Olympic lifts (snatch and clean and jerk) are of special interest [8]. Previous studies investigated the predictive power for top rankings in the CrossFit Games® 2013 and 2016 of the individual benchmark performance, and found no significant results [9,10]. The CrossFit Open® is the main opportunity to qualify for the CrossFit Games®. Mangine et al. analyzed the primary success predictor at the 2018 CrossFit Open®, and concluded that body fat percentage had the most significant effect [2]. To predict the 19.1 CrossFit Open® Workout and the WOD "Fran" performances, a further study concluded that absolute VO_2 peak and CrossFit® Total (one-repetition maximum tests for the squat, deadlift, and overhead press) might be influencing factors [11]. Moreover, it was observed that no German athlete has ever won the CrossFit Games® since they began in 2007. On the other hand, the American participants are the best in the world regarding CrossFit® [12]. However, no study has yet investigated significant differences in the athletes' performance profile between both nations, so for the first time, we analyzed the variation between German and American CrossFit® performances.

To f nd valid predictors of CrossFit® performance, only a few studies have been conducted, and they showed conf icting results [13–16]. On the one hand, previous studies investigated the inf uence of the physiological variables of aerobic capacity and anaerobic power, and showed a signif cant inf uence on CrossFit® performance [13,15]. On the other hand, studies have only demonstrated an effect of strength on the performance of the "Grace" and "Fran" WODs, but not for "Cindy" [14]. The examination of the CrossFit® "Murph" challenge (1-mile run, 100 pullups, 200 pushups, 300 air squats, 1-mile run) showed that only the physiological parameter of body-fat percentage was signif cantly related to total "Murph" time [17]. Based on the results of Dexheimer et al. and Martinez et al., the back squat performance may be considered as a major predictor, so in one study, the back squat strength explained 42% of the variance of the "Fran" performance [15]. Martinez et al. found moderate to strong positive correlations between squat variables and performance in the different WODs [16]. In summary, not a single benchmark performance was found with high predictive power for the main CrossFit® WOD performances. We hypothesize that considering the entire benchmark performance prof le, rather than individual variables, will allow us to predict an athlete's performance ability or compare the performance internationally.

Thus, the aim of our study is to analyze the benchmark performance prof le of American and German CrossFit® athletes in detail, and to investigate any signif cant differences. In addition, we wanted to verify individual parameters of the benchmark performance prof le with our data that predicted specif c CrossFit® performance in previous studies [15,16].

2. Materials and Methods

Here, were report the characterization of international CrossFit® athletes' benchmark performance prof le based on the benchmark data of American and German participants collected by using a questionnaire. We compared our results using the online benchmarking tool "BTWB" with over 60,000 data points of certain benchmark performances to determine the benchmark performance prof le. Based on our sample, we asked whether signif cant differences occurred between nations and identif ed benchmark variables predicting others. Our results will allow CrossFit® athletes to rank their performance internationally, identify def ciencies, and predict specif c benchmark variables.

2.1. Participants

To characterize the benchmark performance prof le of American and German CrossFit® athletes, in this study, 162 CrossFit® athletes (male = 66; female = 96) participated from the United States of America (n = 82) and Germany (n = 80). The average age of participants was 32.6 ± 8.2 years. On average, the athletes had a CrossFit® experience of 3.4 ± 1.9 years, with a training scope per week of 6.6 ± 3.5 h (see Table 1). The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Institutional Ethics Committee of University of the Federal Armed Forces Munich, Germany.

Table 1. Participant characteristics.

	All	Males	Females	American	German
n	162	66	96	82	80
Age (years)	32.6 ± 8.2	33.9 ± 9.0	31.7 ± 7.5	33.9 ± 8.5	31.2 ± 7.7
Height (cm)	172.4 ± 10.1	179.7 ± 7.5	167.4 ± 8.5	169.2 ± 8.8	175.7 ± 10.3
Weight (kg)	75.3 ± 12.9	84.9 ± 10.1	68.7 ± 10.3	73.4 ± 12.7	77.3 ± 13.0
Training scope per week (h)	6.6 ± 3.5	6.9 ± 3.9	6.4 ± 3.3	6.3 ± 3.0	6.9 ± 4.0
CrossFit® experience (years)	3.4 ± 1.9	3.3 ± 1.9	3.5 ± 1.9	3.5 ± 2.1	3.1 ± 1.8

Note: The values are expressed as mean ± standard deviation (SD).

2.2. Measures

The questionnaire contained 19 items for six overall metrics. Items 1–7 referred to anthropometric data, including gender, age, height, bodyweight, workout volume per week, workout frequency, and years of practice in CrossFit®. Item 8 required a focus on competition. The next items contained the current 1-RM for the common power lifts (bench press, deadlift, back squat, shoulder press), the 1-RM for the Olympic lifts (snatch and clean and jerk), and the running times for 400 m sprint or 1-mile. Finally, participants completed items 17–19 regarding their current times for the three most common "Girl" workouts, "Fran", "Grace", and "Helen".

2.3. Procedure

The questionnaire was prepared in German and English, and both were validated for clarity for four weeks each. After validation, the English questionnaire was distributed in f ve CrossFit® boxes around Austin (Texas, United States of America) to collect the American athletes' data. In the same way, the German questionnaires were distributed in six CrossFit® boxes around Munich and Ratisbon (Bavaria, Germany) to collect the data of the German athletes. To include more participants, the questionnaire was also placed online via the platform www.soscisurvey.de (accessed period from 15 October 2018 to 5 November 2018) and shared in social media groups of the participating CrossFit® boxes. The survey period was four weeks for each. To further interpret the results, the sample's performance prof les were compared using the "BTWB" benchmarking online tool, which includes a data set of millions of CrossFit® athletes worldwide.

2.4. Statistical Analysis

Descriptive statistics were performed on participant characteristics (Table 1) and on performance data. All data are presented as mean ± standard deviation (SD). Potential outliers were inspected using a box plot and excluded for the description of the performance prof les. To obtain more informative benchmarks and arithmetic means, we also calculated percentile values for all performance variables from the sample and the online "BTWB" tool. Percentage thresholds of 1%, 10%, 25%, 50%, and 80% were determined to represent the different performance prof les by gender. Preliminary analyses were conducted to ensure there were no violations of the assumptions of normality and homogeneity of the variance. The normality was tested using the Shapiro–Wilk test and Q–Q plots, and the homogeneity of the variance using the Levene test. An independent sample t-test was conducted to compare the benchmark performance for American and German athletes.

The Mann–Whitney U-test was performed when the assumption of normality or the homogeneity of the variance was violated. Simple Pearson's r correlations were used to determine the associations between all benchmark performance data. R-values of 0.1, 0.3, 0.5, 0.7, and 0.9 were considered small, moderate, large, very large, and extremely large, respectively [18]. For each of the dependent Olympic-lift performance variables, a multiple regression model was created to analyze the inf uence of the independent power-lift performance variables. Each power-lift performance variable with signif cant inf uence ($p < 0.001$) was examined in a single linear regression model to create a predictive model of performance and to evaluate the R^2 to determine the portion of explained variation. The regression assumptions were met by performing tests for multicollinearity using variance inf ation factor values, homoscedasticity using a scatterplot of standardized residuals and predicted values, multivariate normality using Q–Q plots, and linearity using scatterplots. All analyses were conducted with the software package SPSS 25.0 (IBM, Armonk, NY, USA), and the level of statistical signif cance (α) was set at 0.05.

3. Results

The anthropometric data of the participants showed that the training scope per week (h) for males was 0.5 h higher than for females and 0.4 h higher for Germans in the national comparison. The CrossFit® experience (years) average was 3.4 ± 1.9, without any major differences between the subgroups.

In Table 2, all performance data are shown by gender and nationality. When comparing the genders, we found that males' total powerlift performance was 61% higher than that of females, and the total Olympic lift performance was 53% higher. Males reported faster times for all "Girl" WODs, despite the scaled weights. This effect was also evident for all run values, as shown in Table 2. The American athletes showed higher average values for all power-lift and Olympic-lift performances, without higher maximum ranges.

Table 2. Performance data by gender and nationality.

Males	All	Range	American	Range	German	Range
n	66		24		42	
1-RM DL (kg)	172.1 ± 37.4	70–261	184.2 ± 31.6	136–261	165.1 ± 38.9	70–260
1-RM BP (kg)	106.3 ± 21.9	53–160	111.4 ± 18.4	80–159	103.4 ± 23.4	53–160
1-RM BS (kg)	140.8 ± 35.6	30–240	152.3 ± 26.5	93–193	134.1 ± 38.6	30–240
1-RM SP (kg)	70.2 ± 15.7	40–130	76.0 ± 17.2	57–130	66.9 ± 13.9	40–105
Total power lifts (kg)	489.3 ± 100.7	250–765	523.9 ± 82.0	393–715	469.5 ± 105.8	250–765
1-RM SN (kg)	74.2 ± 20.8	30–125	79.8 ± 19.0	52–125	71.0 ± 21.3	30–125
1-RM CJ (kg)	95.8 ± 25.8	40–160	100.4 ± 21.3	52–135	93.2 ± 27.9	40–160
Total Olympic lifts (kg)	170.0 ± 45.3	70–285	180.2 ± 38.7	104–260	164.2 ± 48.1	70–285
FR (s	310.4 ± 134.3	142–720	283.1 ± 116.1	142–480	325.0 ± 143.2	177–720
GR (s)	233.3 ± 101.2	115–430	257.0 ± 112.0	117–430	214.1 ± 92.6	115–390
HE (s)	611.2 ± 127.1	393–902	589.9 ± 150.8	393–902	625.8 ± 110.8	509–900
400 m (s)	76.3 ± 19.6	49–150	78.3 ± 24.1	51–150	75.1 ± 16.8	49–106
1 mile (s)	402.1 ± 80.7	234–570	401.0 ± 82.3	251–540	402.7 ± 81.2	234–570
Females						
n	96		38		58	
1-RM DL (kg)	114.4 ± 22.5	62–170	116.6 ± 22.1	62–170	111.1 ± 23.0	70–170
1-RM BP (kg)	54.3 ± 13.0	27–90	56.1 ± 12.3	27–84	51–7 ± 13.9	27–90
1-RM BS (kg)	92.6 ± 20.2	56–136	96.8 ± 19.4	56–136	86.1 ± 19.9	57–130
1-RM SP (kg)	42.8 ± 10.8	25–90	43.9 ± 11.1	25–90	41.0 ± 10.4	25–80
Total Powerlifts (kg)	304.1 ± 60.2	180–460	313.4 ± 57.2	180–424	289.9 ± 62.6	192–460
1-RM SN (kg)	48.2 ± 12.1	25–80	50.1 ± 11.6	29–77	45.3 ± 12.6	25–80
1-RM CJ (kg)	62.8 ± 14.8	25–102	64.4 ± 14.7	25–102	60.4 ± 14.8	35–95
Total Olympic lifts (kg)	111.0 ± 26.2	55–179	114.5 ± 25.4	55–179	105.7 ± 26.8	60–175
FR (s)	361.8 ± 112.7	142–641	346.3 ± 109.8	142–640	390.3 ± 115.3	238–641
GR (s)	250.6 ± 171.2	100–1200	254.3 ± 187.8	116–1200	267.7 ± 107.0	100–482
HE (s)	698.8 ± 186.1	510–1621	673.5 ± 101.3	510–888	754.5 ± 318.0	532–1621
400 m (s)	93.8 ± 20.9	45–188	94.1 ± 16.5	59–123	93.0 ± 30.4	45–188
1 mile (s)	474.1 ± 85.1	242–800	472.4 ± 64.8	358–720	479.2 ± 129.0	242–800

Note: the values are expressed as mean ± standard deviation (SD). Abbreviations: BP = bench press, BS = back squat, CJ = clean and jerk, DL = deadlift, FR = Fran, GR = Grace, HE = Helen, RM = repetition maximum, SN = snatch, SP = shoulder press.

We next studied whether there were signif cant differences in the performance benchmarks between the nations. The t-test for independent samples showed only a signif cant difference (54.5 kg) for the total power lift performance of Americans (523.9 ± 82.0 kg) and Germans (469.5 ± 105.8 kg) in males ($t(64) = -2.17$; $p = 0.034$), and no signif cant difference for females ($t(94) = -2.33$; $p = 0.062$)—see Figure 1. No other signif cant difference was observed in the Olympic lift performance and in the "Girl" WODs or running times between the nations.

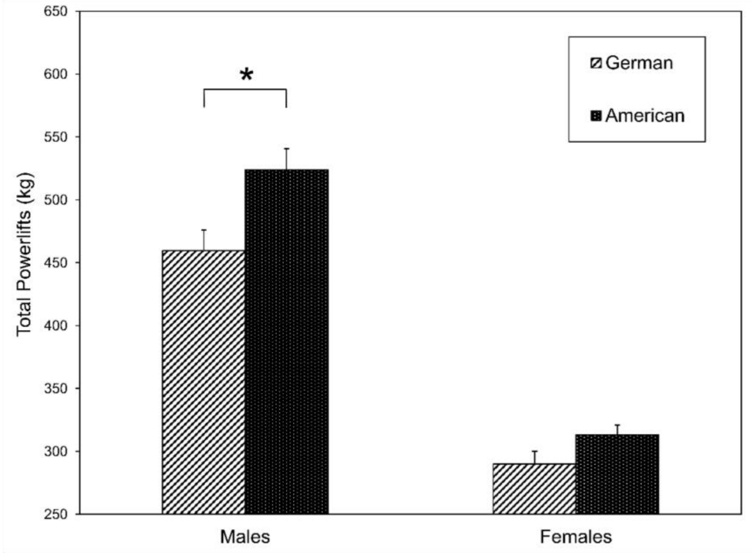

Figure 1. A signif cance difference was found between the total power-lift performances of American and German males ($p = 0.034$), but no signif cant difference was found for females. * $p \leq 0.05$ for American and German Athletes.

The percentage of performance thresholds was calculated (Table 3) and graphically visualized in Figure 1 separated by gender to analyze the benchmark performance prof le. According to percentage threshold values, the classif cation of the performance enabled a more precise description of the CrossFit® athletes' reachable physical f tness. So, females could move less weight in all weightlifting exercises in all performance groups. However, the proportion of the single weightlifting exercises was equally weighted between the genders. So, deadlift performance was the dominant exercise, with a bodyweight ratio of 2.0 for males and 1.7 for females, followed by the back squat performance, with a bodyweight ratio of 1.7 and 1.4, respectively. The bench press performance was not entirely as pronounced in females as in males, with a bodyweight ratio of 0.8 compared to 1.3 (for comparison, see Figure 2A,C). In descending order of expression, the subsequent weightlifting exercises and their bodyweight ratios for males and females were: clean and jerk (1.1 and 0.9), snatch (0.9 and 0.7), and shoulder press (0.8 and 0.6).

Table 3. Percentage thresholds of benchmark performances by gender.

Males	**1%**	**10%**	**25%**	**50%**	**80%**
1-RM DL (kg)	240 (248)	218 (210)	193 (190)	170 (166)	143 (140)
1-RM BP (kg)	142 (161)	130 (134)	120 (120)	105 (102)	85 (84)
1-RM BS (kg)	194 (211)	184 (175)	160 (156)	148 (135)	110 (110)
1-RM SP (kg)	106 (102)	86 (84)	79 (75)	68 (66)	57 (57)
1-RM SN (kg)	125 (120)	100 (98)	90 (84)	70 (70)	60 (57)
1-RM CJ (kg)	134 (145)	125 (120)	115 (107)	95 (93)	75 (77)
FR (s)	175 (139)	184 (187)	204 (247)	274 (337)	424 (479)
GR (s)	115 (95)	119 (131)	142 (163)	203 (214)	322 (313)
HE (s)	393 (442)	455 (507)	515 (556)	602 (630)	682 (753)
400 m (s)	49 (54)	55 (62)	60 (68)	72 (76)	92 (90)
1 mile (s)	234 (312)	303 (351)	340 (378)	413 (416)	472 (482)
Females					
1-RM DL (kg)	170 (160)	145 (134)	130 (116)	111 (102)	98 (84)
1-RM BP (kg)	88 (84)	71 (66)	64 (59)	55 (50)	44 (41)
1-RM BS (kg)	134 (136)	125 (108)	107 (95)	90 (80)	75 (64)
1-RM SP (kg)	57 (57)	52 (48)	48 (43)	41 (38)	35 (32)
1-RM SN (kg)	77 (75)	66 (59)	55 (50)	47 (41)	37 (32)
1-RM CJ (kg)	95 (93)	84 (75)	70 (66)	62 (55)	52 (45)
FR (s)	186 (162)	238 (245)	276 (311)	355 (400)	439 (536)
GR (s)	100 (107)	143 (150)	155 (187)	206 (245)	309 (345)
HE (s)	510 (490)	532 (574)	578 (633)	672 (714)	750 (825)
400 m (s)	59 (65)	75 (77)	82 (84)	90 (95)	109 (116)
1 mile (s)	346 (361)	402 (408)	420 (445)	469 (497)	521 (584)

Note: reference percentage thresholds from the online tool "Beyond the Whiteboard" are in parentheses. Abbreviations: BP = bench press, BS = back squat, CJ = clean and jerk, DL = deadlift, FR = Fran, GR = Grace, HE = Helen, RM = repetition maximum, SN = snatch, SP = shoulder press.

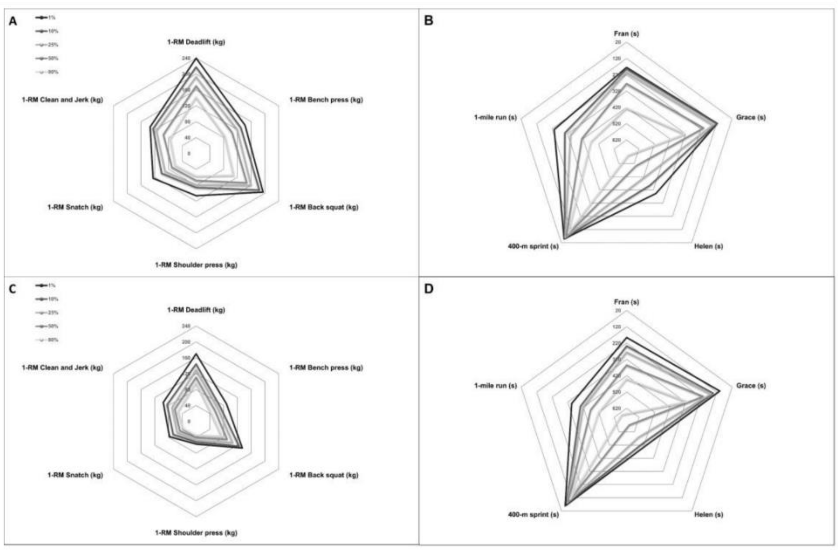

Figure 2. Benchmark performance prof les by gender. The lifting performance of males (**A**) and females (**C**) in comparison shows less total weight for females. The run and "Girl" Workout of the Day performance of males (**B**) and females (**D**) differed only partially.

However, for the "Girl" WOD "Grace," females achieved comparable top performances to males. The difference in mean times was only 1%. Nevertheless, the performance differences in the "Fran" WOD and the 1-mile time were less pronounced than in the "Helen" WOD and the 400 m run time. While females completed the "Fran" WOD an average of 70 s slower, the "Helen" WOD difference was an average of 84 s slower. Similar trends could be observed for the running performance, so the males ran the 400 m on average 25% faster, but the 1-mile only 18% faster.

To analyze the relationship between the benchmark performances, Pearson's correlations were calculated (see Table 4). These signif cant correlations indicated that the power-lift performance was strongly related to the Olympic-lifting performance ($r = 0.79$–0.99; $p < 0.01$). Based on the data of this study, moderate to strong negative correlations between the weightlifting and the "Girl" WOD also were determined, but were partially nonsignif cant (see Table 4). The performance in the "Helen" WOD was strongly related to the performance in the 400 m and 1-mile runs ($r = 0.59 + 0.58$; $p < 0.01$).

Table 4. Pearson's correlation among the performance variables.

	1-RM BP (kg)	1-RM BS (kg)	1-RM SP (kg)	Total PL (kg)	1-RM SN (kg)	1-RM CJ (kg)	Total OL (kg)	FR (s)	GR (s)	HE (s)	400-m (s)	1 mile (s)
1-RM DL (kg)	0.86 **	0.93 **	0.84 **	0.97 **	0.83 **	0.88 **	0.87 **	− 0.47 **	− 0.30 **	− 0.39 **	− 0.50 **	− 0.48 **
1-RM BP (kg)	1	0.84 **	0.89 **	0.94 **	0.79 **	0.82 **	0.82 **	− 0.44 **	− 0.21	− 0.31 *	− 0.44 **	− 0.38 **
1-RM BS (kg)		1	0.84 **	0.96 **	0.87 **	0.92 **	0.91 **	− 0.54 **	− 0.29 *	− 0.40 **	− 0.47 **	− 0.43 **
1-RM SP (kg)			1	0.92 **	0.80 **	0.81 **	0.82 **	− 0.43 **	− 0.12	− 0.37 **	− 0.45 **	− 0.41 **
Total PL (kg)				1	0.87 **	0.91 **	0.91 **	− 0.50 **	− 0.26 *	− 0.40 **	− 0.50 **	− 0.46 **
1-RM SN (kg)					1	0.93 **	0.98 **	− 0.54 **	− 0.24 *	− 0.39 **	− 0.46 **	− 0.41 **
1-RM CJ (kg)						1	0.99 **	− 0.59 **	− 0.31 **	− 0.45 **	− 0.51 **	− 0.46 **
Total OL (kg)							1	− 0.57 **	− 0.28 *	− 0.43 **	− 0.50 **	− 0.44 **
FR (s)								1	0.58 **	0.37 **	0.45 **	0.37 **
GR (s)									1	0.37 **	0.33 **	0.33 **
HE (s)										1	0.59 **	0.58 **
400-m (s)											1	0.81 **
1 mile (s)												1

Note: * signif cant correlation $p < 0.05$; ** signif cant correlation $p < 0.01$. Abbreviations: BP = bench press, BS = back squat, CJ = clean and jerk, DL = deadlift, FR = Fran, GR = Grace, HE = Helen, RM = repetition maximum, SN = snatch, SP = shoulder press.

Based on the Pearson's correlation f ndings, multiple regression was calculated to predict the Olympic lift performance values, snatch, and clean and jerk, based on the single power-lift performance values. From the deadlift, bench press, back squat, and shoulder press performance values, only the back squat performance was a signif cant predictor of snatch and clean and jerk performance ($p < 0.001$). A simple linear regression was performed to predict participant's snatch performance based on their back squat performance (see Figure 3A). A signif cant regression equation was found ($F(1,160) = 497.081$, $p < 0.001$), with an R^2 of 0.756. Participants' predicted snatch performance was equal to 3.333 + 0.494 (back squat performance) kg when back squat performance was measured in kilograms. Participants' average snatch performance increased by 0.494 kg for each kilogram of back squat performance. To predict the clean and jerk performance on the back squat performance, a simple linear regression was calculated in the same way (see Figure 3B). The regression equation was also signif cant ($F(1,160) = 852.916$; $p < 0.001$), with an R^2 of 0.841. The predicted clean and jerk performance was equal to 3.279 + 0.650 (back squat performance) kg. For each kilogram of back squat performance, the clean and jerk performance increased 0.650 kg.

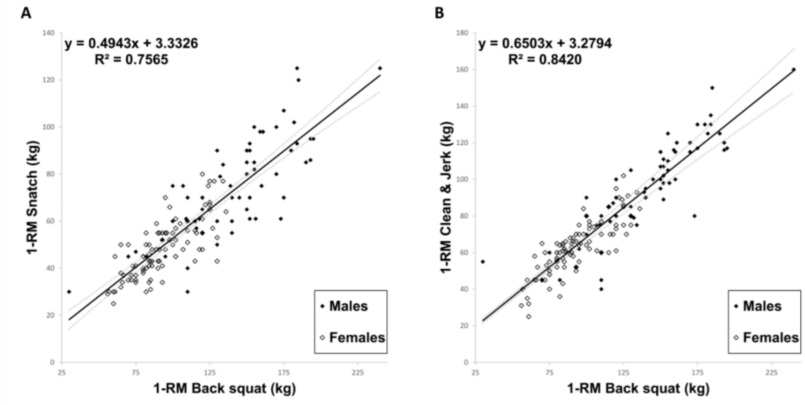

Figure 3. Relationship between the 1-RM back squat performance (kg) and the 1 RM snatch (kg) (**A**), and the 1-RM Clean and Jerk (kg) (**B**) by gender. The continuous line represents the line of best f t, and the dashed lines the 95% conf dence intervals for each correlation.

4. Discussion

In this study, we characterized in detail the benchmark performance prof le of American and German CrossFit® athletes and compared the obtained data with thousands of available online data. We found only one signif cant difference, in the total power-lift performance of males between both nations. Based on our data, the power-lift and Olympic-lift variables showed very large to extremely large correlations. The back squat performance predicted 76% of the variance for the snatch performance, and even 84% of the variance for the clean and jerk performance.

To our knowledge, no studies have previously examined the benchmark performance prof le of CrossFit® athletes in detail. For the f rst time, we were able to describe the overall performance ability of CrossFit® athletes and to identify differences between two nations. Mangine et al. presented normative scores for f ve common benchmark workouts (i.e., "Fran", "Grace", "Helen", "Filthy-50", and "Fight-Gone-Bad") in a previous study, and observed that, on average, males achieved better scores than females for all WODs, despite scaled weights by gender [19]. However, the classif cation of performance by percentage thresholds in this study showed that females may well be able to achieve similar values to males in WODs without bodyweight exercises. We were able to show females of the 1% performance group achieved similar values for the "Grace" WOD consisting only of clean and jerk exercises (135/ 95 pounds for males/ females) with scaled weights contrasted with the "Fran" and "Helen" WODs. Both WODs included the bodyweight exercise of pull-ups. Through all performance groups, females could not achieve similar values as males, conf rmed by the data analysis using the online "BTWB" tool.

Finding only one signif cant performance difference between the two nations was surprising. This result did not conf rm our assumption that the two nations' different levels of success in the CrossFit Games® would result in differences in f tness abilities. So, there could be other factors, such as social capital [20] or commercial environment, to achieve and sustain top athlete success as in other sports; e.g., in tennis [21].

Determining which variables predicted the performance of one of the best-known WODs, "Fran", was also the purpose of previous studies. Leitão et al. showed that maximal and endurance strength training of thrusters was strongly related to "Fran" performance [22]. We can conf rm moderate to strong negative correlations between weightlifting exercises and the "Girl" WODs "Fran", "Grace", and "Helen", also in a multinational experimental group with a larger sample size, as in previous studies.

Our linear regression model was consistent with previous studies demonstrating back squat strength, explaining 84% of the variance for 1-RM clean and jerk performance and

76% of the variance for the snatch performance [14,23]. Thus, to the best of our knowledge, our regression model best describes the variance of snatch and clean and jerk performance of all existing studies regarding CrossFit®. Of note was our large sample size (n = 162), which distinguished our regression model from the noted experimental studies [15,16]. Martinez examined the inf uence of squat performance and performances in different WODs and found moderate to strong ($r = 0.47–0.69$, $p < 0.05$) positive correlations, as our data also showed [16]. This underlined squat as a major determinant of performance in CrossFit®.

However, CrossFit® WODs often consist of multimodal exercises that include not only strength- and power-based actions, but also aerobic exercises like rowing or running. Thus, CrossFit® is a complex training modality that requires different physical abilities (including stamina, f exibility, and agility). So, the interaction of different performances might play a role in the overall assessment of CrossFit® athletes' f tness abilities. For this reason, the total benchmark performance prof le should be considered and combined with the assessment of other physical tests, such as the squat test from Martinez et al. [16].

While the present investigation provided some information about the benchmark performance prof le and the relationship between the performance values, it was not without limitation. Since the present study was only a questionnaire survey, it is unknown whether the results could be reproduced in a performance test. However, the performance prof le can be validated by comparing it with the data from the online "BTWB" tool. Due to the large size of the online data set, possible incorrect data did not have a signif cant impact.

The training concept of CrossFit® intends to optimally prepare the athletes for unknown and unknowable challenges, and how they face them in competition. Identifying predictors for best performance in unknown challenges remains the major task of future CrossFit® science. Our results conf rmed the major role of back squat performance, and showed no differences in physical ability between German and American athletes. Further research should also apply cluster analysis, as shown by Peña et al., to f nd relationships between the outcome of a simulated CrossFit® competition, anthropometric measures, and performance variables [24].

5. Conclusions

To better understand CrossFit® performance, it is necessary to determine a CrossFit® benchmark performance prof le, as we have presented in this study. In future studies, the consistency of the benchmark performance prof le could be conf rmed by experimental data collection. In summary, the prof le allows our results to rank CrossFit® performance internationally, identify def ciencies, and predict specif c benchmark variables.

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8 Purchasing Behavior and Use of Digital Sports Offers during SARS-CoV-2 Lockdown

Full title:

Purchasing behavior and use of digital sports offers by CrossFit® and weightlifting athletes during the first SARS-CoV-2 lockdown in Germany

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Purchasing behavior and use of digital sports offers by CrossFit® and weightlifting athletes during the first SARS-CoV-2 lockdown in Germany

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Abstract

Background: To combat the spread of SARS-CoV-2, CrossFit® training centers, and fitness studios were closed during the first lockdown in Germany from mid-March until June 2020, and as a result, CrossFit® (CFA) or weightlifting athletes (WLA) faced a major challenge for the first time. Therefore, this study aimed to investigate the impact of the first lockdown on the training behavior and to analyze the way the athletes dealt with the new situation. In detail, we focus on habits of purchase and examine the acceptance of digital sports offers between CFA and WLA in response to the restrictions of the nationwide lockdown.

Methods: An online survey was used to characterize the purchasing behavior and use of digital sports offers of CFA and WLA. In total, 484 volunteers (192 women, 290 men, 2 diverse) responded to the online questionary, allowing us to identify changes in training behavior and differences between the sports disciplines.

Results: Our data shows both CFA and WLA purchase new equipment for a home gym and the use of digital sports increased significantly across all age groups. A comparison during the lockdown even showed that within the CFA, one group ($n = 142$) reported losing 5 kg or more of body mass, while the value of the WLA remained constant. On the one hand, the results indicate that despite the restrictions during the lockdown, CFA were may able to enhance health aspects by improving their body composition. On the other hand, this study shows that the training habits of both groups of athletes have changed significantly with the use of digital sports offers.

Conclusions: We suppose that the great openness and the expansion of online sports offers during the first lockdown may change the sports industry in the future.

Keywords: CrossFit® performance, Weightlifting, COVID-19, Lockdown, Physical activity, Public health

Key points

- This study characterizes the first time the purchasing behavior and use of online sports offers of CrossFit® (CFA) or weightlifting athletes (WLA) by an online survey due to the closure of CrossFit® training centers and fitness studios to combat the spread of SARS-CoV-2 in Germany from mid-March to June 2020.
- The analysis of the data of 484 participants provides three significant changes comparing the training behavior before and during the first lockdown, first both athletes CFA and WLA bought new equipment for a home gym, second, the usage of digital sport

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offers increased, and a large group of CFA (n = 142) documented a weight loss of 5 kg and more.
- In conclusion, our data shows despite the restrictions during the COVID-19 lockdown CFA were able to achieve positive effects by practicing the CrossFit® sport and participating in digital sports offers.

Background

To prevent the spread of SARS-CoV-2, all CrossFit® training facilities, and fitness studios were closed during the first lockdown in Germany, resulting in considerable restrictions with so far unknown consequences in practicing CrossFit® and weightlifting. While opportunities for public physical activity have been limited and the focus on improving health through physical activity may have been overshadowed by the combat against the COVID-19 pandemic, we will present how CrossFit® athletes (CFA) and weightlifting athletes (WLA) handle the situation during the first lockdown in Germany [1].

Within a period of only a few months, the SARS-CoV-2 virus has managed to spread across the world. This virus can spread by close contact, which includes large droplet spray and inhalation of microscopic droplets. The typical transmission routes of novel coronavirus include direct transmission (cough, sneeze, droplet inhalation transmission) and contact transmission with oral, nasal, and eye mucous membranes [2]. The fast-spreading of SARS-CoV-2 is also caused by a transmission that starts already two days before symptoms occur or even during infection without symptoms [3]. Government-imposed social distancing has become one of the primary ways of reducing the speed of spreading in many countries in recent months. The closing of all non-essential businesses is a central factor within this strategy [4]. Such non-essential businesses also include fitness studios and CrossFit® training centers. In mid-March, the first lockdown due to the COVID-19 pandemic was declared in Germany's federal states with a slightly noticeable offset [5]. The closure of the sports facilities lasted until June. Weightlifting and CrossFit® athletes did not have the opportunity to train as usual for around three months. From June onwards, strict restrictions still applied, which did not allow a return to the regular training as before [6].

The high-intensity interval training (HIIT) concept CrossFit® focuses on constantly varied functional movements executed at a high intensity. The training includes exercises from the main elements of gymnastics (e.g., Pull-Ups, Push-Ups, and Burpees), weightlifting (Power lifts, e.g. Back Squats, Deadlifts, and Olympic lifts, e.g., Snatch, Clean and Jerk), and cardiovascular activities (e.g., running, rowing, and jumping) usually performed as "workout of the day" (WOD) [7]. CrossFit® training is usually offered in affiliated training centers, where the required and extensive equipment (e.g., dumbbells, barbells, kettlebells, boxes, and jump ropes) and exercise machines such as rowing machines, air bikes and pull up bars are available. Nevertheless, the variety of CrossFit® training content allows athletes to train with considerably less equipment, e.g., only with body weight exercises, running, and jumping [8]. In contrast, weightlifting training emphasizes the use of free weight equipment (e.g., dumbbells and barbells) or weight machines to provide resistance to the exercise movement [9, 10]. Therefore, a minimum equipment with weights is essential for WLA. In limited cases, CFA are able to train without equipment, however, a entire CrossFit® training requires a full range of exercise equipment. Furthermore, access to high-weight equipment is a known problem for WLA [11]. Thus, both CFA and WLA are significantly affected by the closure of the fitness facilities in the execution of their regular training.

In history CrossFit® developed as a new trend sport in a short period of time, digital sports offerings and the formation of a virtual community contributed significantly to the rapid growth and building of the subculture around the trend sport [12]. So, in general, the training concept CrossFit® has good requirements for providing digital sports offers to train virtual at home and, accordingly we suspect a great openness to digital sports offerings among CFA.

However, to date, the impact of the training facility closures for CFA and WFL is unknown. Related studies of changes in training behavior in other sports in Europe report, for example, that the lockdown during the COVID-19 pandemic led to reduced training behavior overall among Spanish basketball players or reduced training time on the ball by Austrian soccer players [13, 14]. We assume that the athletes of both sports have equipped themselves with equipment during the lockdown to train as usual at home. However, the absence of the CrossFit® community in the training facility might be a potential influencing factor to affect training behavior or participation in digital training offerings.

We, therefore, ask, how the nationwide lockdown in Germany from mid-March until June 2020 chances the training behavior of CFA and WLA. To provide a detailed insight into how the athletes dealt with the new situation and to identify the differences between the disciplines, we report a characterization of the purchasing behavior and use of digital sports offers by CFA and WLA during the first SARS-CoV-2 lockdown. In addition, based on our online survey, we present differences in training frequency and changes in body mass during this period.

Methods

Data collection procedure by online survey

To characterize the training behavior of CFA and WLA before and after the first lockdown in Germany, the study was conducted using a common online survey tool that met the university's ethics and privacy policy. For investigation, we developed a questionnaire based on standardized scales and the current state of the literature and validated by fifteen sports scientists according to the method of Gravettter and Forzano [15]. Following validation and two months after the first lockdown was declared in Germany, the questionnaire was online available at www.soscisurvey.de for 16 days (18th of May till 2nd of June 2020), and the link was shared on local CrossFit® platforms, Weight training platforms, and social media.

Measurements

The first item on the questionnaire included a choice question about which sport the participants performed, CrossFit®, weightlifting, or neither. Thus, the participants were selected on the criteria of performing any of both sports. After collecting common anthropometric and demographic data, the participants were asked about their training behavior and reason for sport in the previous period of the first lockdown and during the current lockdown period, which began in Germany on March 15, 2020. To analyze changes in purchasing behavior and use of digital sports offerings before and during the first lockdown, the survey includes items regarding equipment at home and attendance and motivation for digital sports.

Statistical analysis

All data are presented as mean ± standard deviation (SD). For data interpretation, IBM SPSS version 26 (IBM, Armonk, NY, USA) was used. The normality was tested using the Shapiro–Wilk test and Q–Q plots. For the test of sampling adequacy, a Kaiser–Meyer–Olkin (KMO) analysis was performed. To compare the training behaviors, normally distributed variables were analyzed using the Students T-Test. For ordinal scaled or non-normal distributed variables, Mann–Withney-U tests were carried out. Nominal-scaled variables were analyzed using Chi-square. The level of statistical significance (α) was set at 0.05.

Results

Demographic and anthropometric data of the participants

To characterize the impact of the first lockdown on the training behavior, in total, 484 athletes (59.9% men, 39.7% women, and 0.4% diverse) practicing CrossFit® or weightlifting participated in this survey. The average age was 31 years (range 18–65 years), with comparable average ages between males (18–65 years) and females (19–63 years). Demographic data showed that most participants had higher education and more than half were employees, while 1/3 were students, with an average weekly working time of all participants of 37 h before the COVID-19 pandemic. A detailed overview of the descriptive athlete's characteristics is given in Table 1.

While most participants trained three or more days per week for more than two years, of those 266 reported CrossFit® [hereafter referred to as CrossFit® athletes (CFA)] and 218 reported weightlifting [hereafter referred to as weightlifting athletes (WLA)] as their primary sport. Since the study aims to characterize the effects of the first lockdown by showing the differences in the behavior of CFA and WLA, we first present the comparison between the two groups in order to be able to show the different changes due to the restrictions.

Comparison of athletes doing CrossFit® or weightlifting

Our data shows that women did more likely CrossFit® and men weightlifting ($p < 0.001$). Regardless, both groups had comparable training experiences, and most of them had an experience of more than two years ($p = 0.055$). Although CFA had significantly higher working time ($p = 0.003$) before the first lockdown, however, both groups had similar working times during the lockdown ($p = 0.164$). In comparison, CFA trained more days per week ($p = 0.04$) before the first lockdown as well as during the first lockdown ($p = 0.005$), see Table 2.

In Addition, athletes were asked about additional sports before and during the lockdown. The results indicate that 53% of the CFA and 42.2% of the WLA did not do any additional sport besides their main sport before the lockdown. Whereas 25.2% of the CFA and 27.5% of the WLA performed endurance training additionally.

Changes during the first lockdown

Three significant changes were observed compared before and during the first lockdown. Athletes bought new equipment for a home gym, the usage of digital sport offers increased, and a large proportion documented a weight loss of 5 kg and more. All these three observations were associated with their weekly training frequency. Most athletes who bought new equipment for a home gym (36%) trained 5 days or more per week before the lockdown (Fig. 1A) as well as during the lockdown (31%) (Fig. 1B).

The training frequency of the athletes who did not buy any equipment did not change significantly before the lockdown vs during the lockdown; this group (31% and 29%) continued to train mainly 3 days per week (Fig. 1A, B). The number of athletes (27%) who trained 4 days a week before the lockdown and bought equipment

Table 1 Overview about demographic and anthropometric data of the participants

	Total	Women	Men	Diverse
Completed questionnaires	100% (484)	39.7% (192)	59.9% (290)	0.4% (2)
Age (years)	31 (18–65)	33 (19–63)	29 (18–65)	32 (31–33)
Hight (cm)	176 (155–201)	168 (155–188)	181 (167–201)	162 (160–164)
Weight (kg)	76 (48–130)	65 (48–116)	84 (57–130)	69 (57–80)
Educational degree				
Secondary school	3.5% (17)	4.7% (9)	2.7% (8)	–
Completed vocational training	6.4% (31)	7.8% (15)	5.5% (16)	–
High school	28.9% (140)	18.8% (36)	35.9% (104)	–
Bachelor	25.0% (121)	23.4% (45)	26.2% (76)	–
Master	33.1% (160)	42.2% (81)	26.9% (78)	50% (1)
Doctor	3.1% (15)	3.1% (6)	2.8% (8)	50% (1)
Employment				
Student	33.0% (160)	21.3% (41)	41.0% (119)	–
Employee	53.1% (257)	62.5% (120)	46.6% (135)	100% (2)
Official	8.3% (40)	9.4% (18)	7.6% (22)	–
Self-employed	4.5% (22)	5.2% (10)	4.1% (12)	–
Homemaker	0.4% (2)	1.0% (2)	–	–
Pensioner	0.2% (1)	0.5% (1)	–	–
Unemployed	0.4% (2)	–	0.7% (2)	–
Income, net monthly (€)				
Less than 500	1.2% (6)	2.1% (4)	0.7% (2)	–
500–1500	9.7% (47)	11.5% (22)	8.6% (25)	–
1500–2500	37.4% (181)	34.9% (67)	39.0% (113)	50.0% (1)
2500–3500	30.0% (145)	27.6% (53)	31.7% (92)	–
3500–4500	8.3% (40)	8.3% (16)	8.3% (24)	–
4500 and more	4.8% (23)	3.6% (7)	5.2% (15)	50.0% (1)
Not specified	8.7% (42)	12.0% (23)	6.6% (19)	–
Regular working time per week (h)	37 (0–60)	39 (0–60)	37 (0–60)	40 (39–40)
Training experience				
Less than 3 months	3.1% (15)	0.5% (1)	4.8% (14)	–
3–6 months	5.8% (28)	4.4% (8)	6.9% (20)	–
6–12 months	9.5% (46)	11.5% (22)	8.3% (24)	–
12–24 months	17.1% (83)	21.9% (42)	14.1% (41)	–
More than 24 months	64.5% (312)	62.0% (119)	65.9% (191)	100% (2)
Training days per week				
1	3.9% (19)	3.1% (6)	4.5% (13)	–
2	14.9% (72)	16.1% (31)	14.1% (41)	–
3	29.8% (144)	31.8% (61)	27.9% (81)	50% (1)
4	26.4% (128)	26.0% (50)	26.9% (78)	–
5 and more	25% (121)	22.9% (44)	26.6% (77)	50% (1)

If units are given, first value shows the mean, and the range is given in brackets. For the rest the percentage is given, and the total number is given in brackets

for a home gym decreased during the lockdown (20%) (Fig. 1A, B). Most athletes who used digital sports offers trained 3 days a week before the lockdown (35%) versus 26% during the lockdown. Those who trained 5 days and more a week before the lockdown (23%) and used digital sports offers also trained 5 days or more per week during the lockdown (23%) (Fig. 1C, D). Most athletes who lost 5 or more kg of body mass during the lockdown trained 5 days or more per week before (35%) as well as during the lockdown (34%) (Fig. 1E, F).

The practice of additional sports also shifted during the lockdown in a manner that the percentages of athletes not practicing additional sports decreased to 49.6% of CFA and 39.0% of WLA, and the percentages of athletes

Table 2 Comparison of attendees doing CrossFit® or weightlifting as a primary sport

	CrossFit®	Weightlifting	*p* value
Gender			< 0.001
Women	68.2% (131)	31.8% (61)	
Men	45.9% (133)	54.1% (157)	
Diverse	100% (2)	0% (0)	
Training experience			0.055
Less than 3 months	2.6% (7)	3.7% (8)	
3–6 months	4.9% (13)	6.9% (15)	
6–12 months	12.0% (32)	6.4% (14)	
12–24 months	19.9% (53)	13.8% (30)	
More than 24 months	60.5% (161)	69.3% (151)	
Working time per week (before)			0.003
Less than 10 h	1.6% (4)	1.9% (4)	
10–19 h	2.0% (5)	6.1% (13)	
20–29 h	10.6% (27)	9.9% (21)	
30–39 h	26.8% (68)	39.0% (83)	
40 h and more	59.1% (150)	43.2% (92)	
Working time per week (during)			0.164
Less than 10 h	8.6% (22)	3.8% (8)	
10–19 h	8.2% (21)	9.9% (21)	
20–29 h	12.1% (31)	10.8% (23)	
30–39 h	27.0% (69)	33.5% (71)	
40 h and more	44.1% (113)	42.0% (89)	
Training days per week (before)			0.04
1	2.6% (7)	5.5% (12)	
2	14.7% (39)	15.1% (33)	
3	27.4% (73)	32.6% (71)	
4	25.2% (67)	28.0% (61)	
5 and more	30.1% (80)	18.8% (41)	
Training days per week (during)			0.005
1	9.1% (21)	9.1% (17)	
2	15.5% (36)	20.4% (38)	
3	25.4% (59)	29.0% (54)	
4	18.5% (43)	25.8% (48)	
5 and more	31.5% (73)	15.6% (29)	
Additional sports (before)			0.004
None	53.0% (141)	42.2% (92)	
Endurance	25.2% (67)	27.5% (60)	
Ballgames	7.5% (20)	12.8% (28)	
Climbing	0.8% (2)	3.2% (7)	
HIIT, other	0.8% (2)	0.9% (2)	
Fight sport	2.6% (7)	6.4% (14)	
Dancing	2.3% (6)	2.8% (6)	
Weightlifting	5.3% (14)	0.5% (1)	
Yoga	1.5% (4)	2.8% (6)	
Others	1.1% (3)	0.9% (2)	
Additional sports (during)			0.003
None	49.6% (132)	39.0% (85)	
Endurance	28.9% (77)	28.9% (63)	
Ballgames	6.0% (16)	12.4% (27)	
Climbing	0.8% (2)	3.2% (7)	
HIIT, other	0.8% (2)	0.5% (1)	
Fight sport	2.6% (7)	5.5% (12)	
Dancing	1.9% (5)	2.8% (6)	
Weightlifting	4.9% (13)	0.5% (1)	
Yoga	2.6% (7)	3.2% (7)	
Home workouts	1.1% (3)	3.2% (7)	
Others	0.8% (2)	0.9% (2)	

p values were calculated using Chi-squared test (before: time before lockdown; during: time during lockdown). If units are given, first value shows the mean, and the range is given in brackets. For the rest the percentage is given, and the total number is given in brackets

practicing endurance training increased analogously to 28.9% and 28.9%, respectively.

General aspects of the two groups of athletes with and without purchased equipment

Athletes were asked if they bought additional training equipment during the lockdown. Those, who bought equipment were more frequently in short-time work (10.2% vs. 3.9%, $p=0.011$) and more likely CFA (49% of all CFA and 39% of all WLA, $p=0.043$). Before lockdown athletes who bought new equipment did more often sports (main group of 35.8% did 5 sessions or more per week, whereas the others did with 30.7% mainly 3 times training, $p=0.016$), but training frequency during lockdown did not show significant differences ($p=0.55$). In addition, a larger proportion in this group went usually to a gym (88.8% vs. 76.2%, $p=0.001$), did less endurance training before the lockdown (40.6% vs. 51.9%, $p=0.021$), less body weight training (33.2% vs. 50.2%, $p\leq 0.001$), and did have had own equipment at home before (27.8% vs. 37.7%, $p=0.033$). Usage of digital sport offers were less often stated (11.8% vs. 19.0%, $p=0.028$), but more often training with a partner (46.5% vs. 36.4%, $p=0.023$).

Digital sports offers depending of training days, age, and nutrition

In the following part, we focused on the use of digital sports offers depending on the number of training days per week, age, and attention to nutrition. For all athletes (CFA and WLA) an increase in using digital sports offers was observable during the lockdown, independent from their training days (except CFA who trained 1 day per week). That increase was higher for CFA. The highest increase was observed for athletes, that trained 2 or 3 days per week. Of the CFA who trained 5 days a week, 15% already took advantage of digital sport offers before the lockdown, while it was 40% during the lockdown. Of

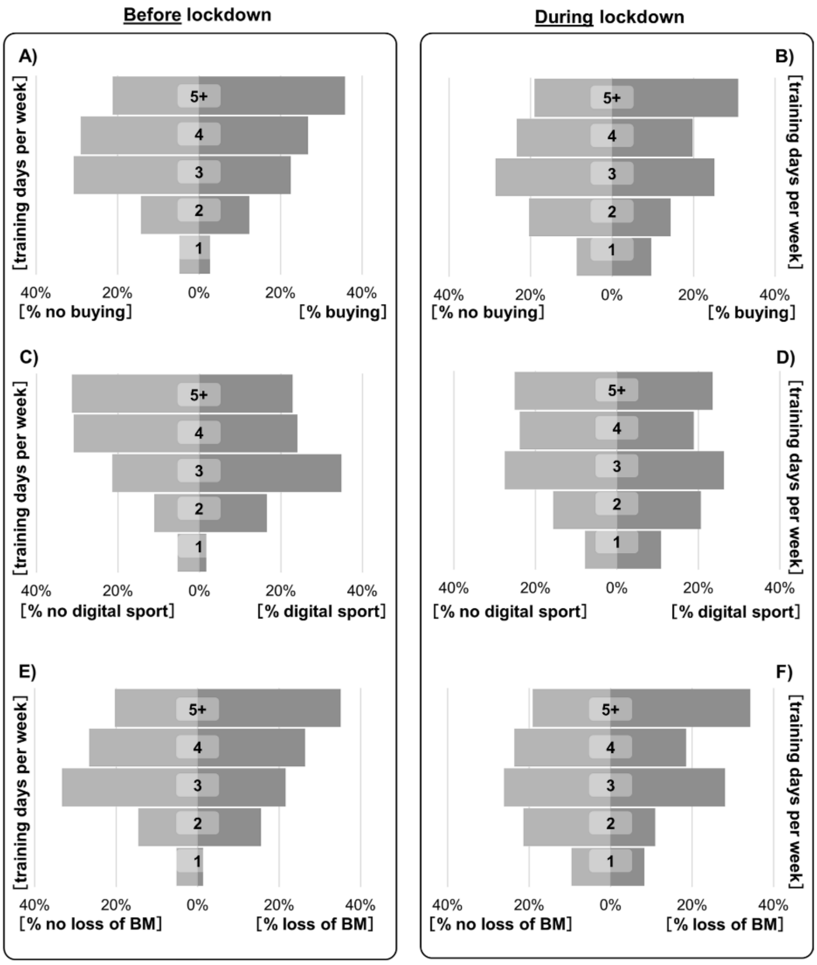

Fig. 1 The training days (1–5 +) of all athletes before (left box) and during (right box) the first lockdown in Germany were analyzed in combination with buying of new equipment (**A**, **B**), usage of digital sport offers (**C**, **D**) and the loss of 5 kg body mass (BM) or more (**E**, **F**)

those WLA who trained 5 days a week, also 15% took advantage of digital sport offers before the lockdown and 24% during lockdown (Fig. 2A, B).

If one looks at the use of digital sports offers in relation to age, it is noticeable that athletes over 55 years of age did not take advantage of digital offers before the lockdown (0%). Among the CFA > 55, usage increased to 50% during the lockdown and remained at 0% for the WLA. Among the under 55-year-olds, 10% of the CFA and 0% of the WLA took advantage of digital sports offers before the lockdown. During the lockdown, usage increased to 53% for the CFA and 100% for the WLA.

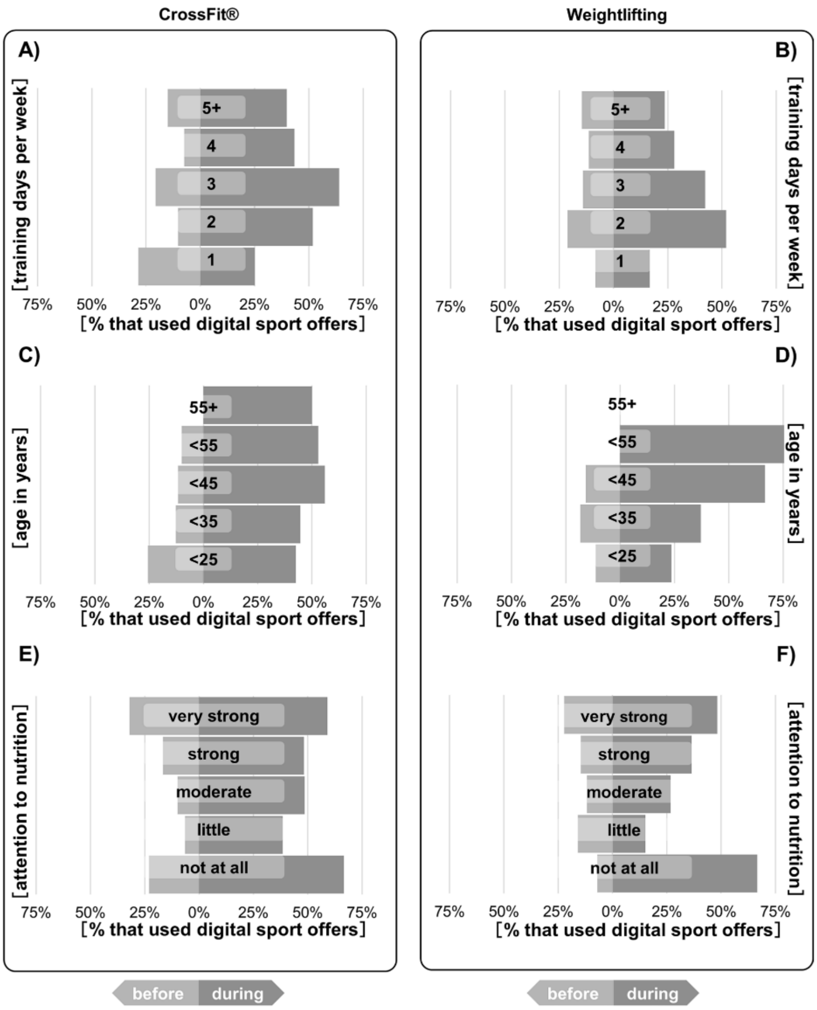

Fig. 2 Usage of digital sport offers before (green bars) and during (blue bars) the first lockdown in Germany (indicated as 'before' and 'during'). Participants were subdivided according to their primary sport (CrossFit® or weightlifting). The groups were separated on the amount of training days before the lockdown (**A**, **B**) the age (**C**, **D**), and how much they pay attention to their nutrition (**E**, **F**)

Among the CFA < 45, 12% used digital sport offers before the lockdown and 56% during the lockdown, among the WLA < 45 were 16% before and 67% during the lockdown. Among the < 35-year-olds, 13% of the CFA and 18% of the WLA used digital sports offers before the lockdown. During the lockdown, it was 45% of the CFA and 37% of the WLA. In the age group < 25 were 26% of the CFA and 11% of the WLA before the lockdown and 43% of the

CFA and 24% of the WLA during the lockdown (Fig. 2C, D). When looking at the use of digital sports offers depending on diet, there was also an increase across all categories. Those CFA who said that they pay attention to their diet "very strong", 32% took part in digital sport offers before and 59% during the lockdown. Of WLA in the same category, 22% took part in digital sports offers before and 48% during the lockdown. The greatest increase was among those CFA and WLA who said they pay attention "not at all" to their diet. Here it was 67% of the CFA and WLA who took part in digital sports offers during the lockdown (Fig. 2E, F).

Losing 5 kg and more body mass

For the majority of the athletes (70% divides into 51% of WLA and 19% of CFA), no change in body mass was recorded. However, what stands out was a group of 142 respondents (29.7%) who practice CrossFit® and who answered they had lost more than 5 kg body mass, see Fig. 3.

This group seemed to be different from the rest (hereafter referred to as CF5). The athletes in the CF5 group were often women (53.3%), which explains why this group is significantly smaller and lighter. The CF5 group were older (33.9 vs 29.0 years, $p < 0.001$) and trained more likely to improve health (81.0% vs 72.0%, $p = 0.039$) and less to build muscles or aesthetics. In CF5, the mean income was higher, but the proportion of people in short-time work (12.7% vs 3.9%, $p < 0.001$) or compulsory leave (7.0% vs 1.8%, $p = 0.004$) because of the lockdown was increased, see Table 3.

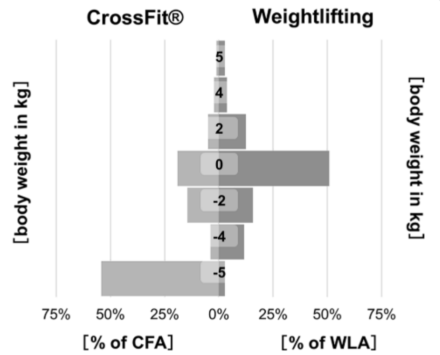

Fig. 3 Distribution of weight changes during the lockdown divided into athletes doing CrossFit® (green bars) or weightlifting (blue bars). Meaning of the numbers within the bars: 5: weight increase by 5 kg and more; 4: weight increase by around 4 kg; 2: weight increase by around 2 kg; 0: 0 kg weight more or less = unchanged; − 2: weight decrease by around 2 kg; − 4: weight decrease by around 4 kg; − 5: weight decrease by 5 kg or more)

Discussion

In this study, we characterized for the first time in detail the changes in training behavior of CFA and WLA during the first lockdown from mid-March until June 2020 of the COVID-19 pandemic in Germany. We found three significant changes comparing the training behavior before and during the first lockdown. First, both CFA and WLA bought new equipment for a home gym, second, the usage of digital sports offers increased, and a large group of CFA documented a weight loss of 5 kg and more. The first lockdown beginning in mid-March 2020 in Germany was the first time that training centers were closed nationwide and, due to the short history of CrossFit®, it was also the first time that athletes could not train as usual in their training centers. So, our study describes for the first time the impact of the first lockdown on CFA and WLA and analyses the differences of the training concepts in this context.

We focused in this study on CFA and WLA as both need a lot of equipment. Garage gyms are very rare in Germany, and people most often perform these sports in sports facilities, where the necessary equipment is available [11]. So, both groups were hard hit by the restrictions to combat the spread of SARS-CoV-2. Therefore, we were interested in how the two groups handled the situation, equally or differently, and what factors might impact possible differences. While weightlifting is usually performed alone or with a partner, CrossFit® is a group sport characterized by strong social interaction and a sense of community [11, 16, 17].

Thus, by comparing both disciplines, our results show that CFA and WLA differ in many ways. As weightlifting has less variation than CrossFit®, those athletes perform additional sports more often, like Endurance and ballgames. CFA are more common women, have longer working hours per week, and train more often per week. CFA's high training volume per week is consistent with previous studies describing over 6 training hours per week on average for German and American athletes [18]. Our survey indicates CFA train more days per week in comparison with WLA, probably caused by shorter workouts or training time per session. In addition to the closing of all non-essential businesses during the first lockdown, many employees used the opportunity to work from home to reduce further personal contacts [19]. We assume that shorter workouts like ultra-short CrossFit® workouts shown by Meier et al. are better integrable into breaks of home office work [20].

Overall, 49% of CFA and 39% of WLA purchase new equipment during lockdown to train at home, in line with

Table 3 Overview about all significant differences of CFA who declared to have lost 5 kg or more (CF5 group) with all the others

	CF5 group	All others	*p* value
Age (years)	33.9 ± 8.4	29.0 ± 7.8	< 0.001
Gender			< 0.001
Women	53.30%	33.60%	
Men	46.50%	65.80%	
Diverse	0%	0.60%	
Height (cm)	173 ± 8.8	177 ± 8.9	< 0.001
Weight (kg)	72.8 ± 12.5	78.0 ± 13.6	< 0.001
Exercises with a partner	54.90%	35.70%	< 0.001
Exercises to build muscle	69.70%	78.60%	0.039
Exercises to improve aesthetics	38.00%	53.30%	0.002
Training-days per week			
Before	3.8 ± 1.1	3.4 ± 1.1	0.004
During	3.6 ± 1.2	3.2 ± 1.4	0.005
Trains to improve health			
Before	81.00%	72.00%	0.039
During	87.90%	78.30%	0.018
Short time work because of the lockdown	12.70%	3.90%	< 0.001
Compulsory leave because of the lockdown	7.00%	1.80%	0.004
Income, net monthly (€)			0.001
Less than 500	2.40%	1.00%	
500–1500	6.50%	11.50%	
1500–2500	31.70%	45.40%	
2500–3500	40.70%	29.70%	
3500–4500	8.10%	9.30%	
4500 and more	10.60%	3.20%	

Before meaning information on the situation before the lockdown; during meaning information on the situation during the lockdown. Values are given as a percentage or mean value with standard deviation

our expectations, as both sports require a large amount of equipment. Due to the large and unexpectedly high demand for sports equipment, it led to up to 90% sold out online and in stores [21]. Due to this fact, our results may show a bias, as not every athlete had the opportunity to purchase new equipment.

An unmistakable trend during the first lockdown was the increasing availability of digital sports content and so, across all age groups, were we able to observe a significant increase in the usage of digital sports offers. To continue offering a variety of exercise and training activities, several digital training tools have been developed to date. Generally, 3 types of offers can be distinguished: live streaming of digital training courses, digital distribution of written training units, and the production of videos that can be viewed by members independent of time [22].

Scientifically, the status of such services is currently unclear. In a systematic meta-analysis, Romeo et al. concluded that digital interventions by smartphone apps have only a nonsignificant, positive influence on measured physical activity [23]. The same is reported in a meta-analysis focused on older persons [24], and in comparison, of several concepts for young adults [25]. This lack of positive physical impact may be because such approaches do not work or are not mature enough. Nevertheless, in 2020 a lot of new digital concepts have come up [26]. Many CrossFit® training facilities were forced to move their service online and as a result, they launched digital training provided to their members. There were also occasional attempts to achieve interactions and connections in the respective groups via virtual platforms and social media [27].

As this is a new and fast-evolving phenomenon, there is as yet no scientific evidence of the value of such services and the benefits that athletes receive. Nevertheless, we observed strong participation of CFA in digital sport offerings, especially among older athletes (> 55 years) who may not have previously experienced these. In contrast, WLA in this age group did not participate in any online sports offers. To explain this result, we suggest that, based on the assumption weightlifting workouts are easier to program than CrossFit® workouts [28], WLA already know how to train themselves without participating in digital sports.

The larger acceptance of digital sport offers reflects a higher sense of community among CFA and strong social interaction, in accordance with previous studies [16, 29]. A related conclusion was reached in the study by Redwood-Brown et al. so far. They reported that athletes who were already practicing CrossFit® before had not altered their training behavior during the lockdown, a fact they attributed to the increased adherence associated with CrossFit® [30]. This is consistent with further findings suggesting that one of the most important interventions for a CrossFit® training facility should be, especially during the COVID-19 pandemic, to establish a Facebook and Instagram community for its members. These online communities have been shown to provide great value to the athletes both before and during the lockdown, such as social and motivational benefits [27, 31].

Another factor that may explain the increased use of digital services of CFA is that a variety of gymnastics and cardiovascular exercises can be adapted to train at home [32], while WLA relies heavily on free weights or weight machines, which were only partially available at home. Thus, we hypothesize that, in addition to the sense of community, the modality of online training and the practicability at home influence on participation, although based on our data, where we did not determine the specific requirements of the digital training athletes participate in, we are unable to answer this question.

The most surprising result of our study was that one group of CFA (n = 142) achieved a weight loss of 5 kg or more. Interestingly, the majority of this group were women and trained CrossFit® to improve their health. For this reason, we assume, that the group of CF5 may improve their body composition in contrast to the general population, which is characterized by increased physical inactivity during the lockdown, resulting in weight gain and other negative health effects [33, 34]. To consider probable explanations for the weight loss results of group CF5, other influencing factors may need to be included. So, a study regarding behavior change during COVID-19 pandemics found that the group that was more active during the lockdown also changed their dietary habits toward a healthier profile [35]. As our data also show that group CF5 spent more time at home due to increased short-time work or compulsory leave as a result of the lockdown, we suspect that more time and focus on a healthier lifestyle as well as increased CF training time may have resulted in this outcome. Nevertheless, due to the restrictions of the first lockdown were are unable to verify the weight changes of CFA by measurements, which affects the conclusion of our study. However, despite this, both types of athletes usually track their body mass very detailed, so our data provide a helpful assessment of how the restrictions of the first lockdown impacted a number of the CFAs we studied.

The trend towards training at home experienced a massive increase during the lockdown, and we were also able to observe this during this survey. For this reason, the study is not without limitations, despite the novel findings. What we had not considered while designing the study was the extraordinary situation that many sports equipment retailers had sold out their everyday items for months. Thus, has undoubtedly had an impact on the number of purchases.

Overall, our results indicate potential benefits in CrossFit® and weightlifting sport during the fist lockdown, so we suggested that practicing CrossFit® may improve body composition despite the restriction to combat the spread of SARS-CoV-2. In general, we emphasize here the positive health aspects of practicing CrossFit® or weightlifting as opposed to overall observations regarding the physical activity of adults during lockdown [36]. In addition, increased digital sports offerings allow training facilities to reach more potential customers [37], and athletes have the opportunity to perform CrossFit® regardless of where they are located. In Particular, in CrossFit® sport, our results show a great acceptance of digital sport offers, across all ages groups. However, evidence of the positive physical effects and performance enhancement of digital sports is still missing. In future studies, digital sport offers also need to be examined regarding the risk of injury. We are unable to comment based on our data. However, considering the benefits and limitations of digital sport offers, it's important to be noted that especially in CrossFit®, training at home without an on-site trainer may lead to increased injury rates [38].

Conclusions

The reason for our study was the closure of fitness facilities purposing social distancing during the first lockdown, which appears to be an essential step to slow down the spread of SARS-CoV-2. However, it is still unclear what role fitness facilities and CrossFit® training centers play in terms of distribution. Moreover, the authors Gil et. all demonstrate that physical strength and increased muscle power, which can be improved by both CrossFit® and weightlifting, allows a better recovery from a COVID-19 infection [39]. Therefore, we emphasize the importance of maintaining exercise and training behavior, e.g., through digital sports offers as shown by our data, especially in times of global pandemic.

Our study shows that the changes in the training behavior of CFA and WLA due to the restrictions to combat the spread of SARS-CoV-2 have opened opportunities for CrossFit® and weightlifting sports which may become even more important in the future. So, it opened new opportunities for training facilities to expand their offerings and reach more potential customers through digital sports services. Our data show that especially among CFA, digital sports offerings were accepted across all age groups. Since digital training can be participated from anywhere, we assume the importance will increase in the future due to business trips, vacations, increasing mobility. In summary, digital sports offers every athlete the opportunity to practice CrossFit® and benefit from positive effects on health, regardless of their location and regardless of whether there is a training center on location.

Abbreviations

CFA: CrossFit® athletes; CF5: CrossFit® athletes who lost 5 kg body mass; HIIT: High-intensity interval training; KMO: Kaiser–Meyer–Olkin; SD: Standard devison; WLA: Weightlifting athletes; WOD: Workout of the day.

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Authors' information

Annette Schmidt is a CrossFit® Level 2 trainer and the owner of a military affiliate. She is allowed to use the term CrossFit®.

Authors' contributions

NM prepared the manuscript and wrote the original draft. AS and NM designed the conceptualization and the methodology of the study and, TN and RW performed data collection. Investigation, statistical analysis and interpretation of the results were performed by AS and NM. AS reviewed the manuscript and provided administrative oversight. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Ethics Committee of the University of the Bundeswehr Munich, Germany (06/04/2018). From all participants and, if subjects are under 16, from a parent and/or legal guardian consent was obtained before participation in the online survey.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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9 Conclusion and Outlook

In this thesis, specific knowledge gaps in the field of CrossFit® science were filled. So far, the training concept of CrossFit® is characterized in scientific literature as FFT with homogenous physiological demands and responses to different WODs (62), however, without an overview of performance profiles and no consensus on which parameters offer an advantage in competition (28). Also, the implications of the restrictions imposed on athletes by combating the spread of SARS-CoV-2 remains poorly characterized to date (20, 21, 159). Thus, within the presented research projects, this thesis contributes to major challenges in CrossFit® science by characterizing (a) physiological and cardiovascular parameters during short and long training durations, (b) a Benchmark performance profile and performance predictors, and (c) changes in training behavior during the COVID-19 pandemic. So, new insights into the nature of CrossFit® are provided.

To respond to one of the specific research questions, a pilot study was intended to show what physiological parameters occur after an ultra-short, intense CrossFit® workout lasting less than 2 min. Thereby, for the first time, a time-delayed increase in blood lactate values was observed after an ultra-short CrossFit® workout, as known so far only from other sport types, for example, in response to short runs, see **chapter 5** (165). The results also attest to the fact that physiological responses similar to running are induced within the CrossFit® training program while requiring much less training area. The study tie in with the investigations of Tibana et al. on a shorter (~ 4 min) CrossFit® workout (93) and underline that high blood lactate levels are achieved with a time lag during ultra-short workouts. The study design provided for the measurement of the individual LTPs of the participants and therefore allows the representation of the lactate values in relation to the LTPs, resulting in closer intra-sample comparability of the data. However, to evaluate the data in relation to the results of other studies, the determination of the individual LTPs of the participants prior to blood lactate measurements might be beneficial in future research approaches. Since existing scientific data on the physiological response to CrossFit® training rarely include the determination of LTPs, the advantage of the procedure is particularly mentioned. The measured RPE values of 8.1-17.4 were consistent with reports in the CrossFit® literature, commonly referring to very high RPE values, ranging from 5.4-9.6 from a maximum of 10 points (54, 88, 93, 94, 101, 105), although a deviating scale of 6 to 20 was applied in the study. For uniform reporting, the use of the more common 0-10 scale is recommended in further research.

Given the limitation that the pilot study only examined physiological responses after an isolated ultra-short, intense WOD and not after an entire CrossFit® training session, the follow-up investigation contributes to address this research gap. A recent publication as well emphasized the point that the terminology used for the conducted research needs to be more precise (17). In this manner, in recent years, a variety of terms used to describe different types of fitness training, including CrossFit®, HIFT (26), HIMT (39), FFT (17), extreme conditioning program (170), and Mixed Modal Training (171) in practice and scientific research. Sometimes the terms are used to describe the same basic training principles, but other times they are used to mean different types, complicating appropriate research and evidence-based recommendations. For this reason, this work referred that the scientific characterization focuses on the principles of the CrossFit® brand and therefore the term CrossFit® is appropriately assigned. Nevertheless, the opinion of the article by Dominski et al. is supported that a separate analysis of an isolated WOD that includes solely metabolic conditioning training does not comprehensively reflect the training practices of the sport of CrossFit® (17). Since this thesis aimed to characterize the CrossFit® training program in broad terms, an observational study was conceptualized to describe physiological demands in practical settings.

In this regard, what cardiovascular responses occur under real training conditions and how different levels of CrossFit® experience impact, were answered by an observation of a series of four different 1-h CrossFit® training sessions. Thereby, the measurement of HR values in 1-h training sessions allows the conclusion that the assumption that CrossFit® training is performed predominantly in the HR range above 90% of HR_{max} is misunderstood in the scientific literature (62). In contrast, the results show that with 1-h training sessions, HR reached values above 90% of HR_{max} solely during the performance of the WOD, see **chapter 6**. After the submission of the presented data of performing CrossFit® in 1-h sessions divided into separate training parts, a similar study was published by Dias et al. (172). Thereby, the analysis shows that in seven non-consecutive CrossFit® training sessions divided into mobility, warm-up, skill, and workout segments, HR values significantly increased during each segment and fell below the peak HR value of the previous segment, indicating that the time spent switching between training segments affected the average HR of the entire session. The conclusions are consistent with the results of this thesis. In this context, monitoring HR values of 1-h CrossFit® sessions may help coaches to program the content of training sessions and to verify that athletes are not overwhelmed. In addition, the findings of this thesis demonstrate that by the scalability of the training programming the beginner and experienced CrossFit® athletes, regardless of their individual CrossFit® experience, were able to complete the same training session and exercise to maximal capacity with no significant differences in cardiovascular responses to the training stimulus. However, for a better understanding of how the CrossFit® training concept works the physiological evaluation of isolated WODs is insufficient and more research needs to be conducted on the practical implementation of the training concept in the future. This investigation demonstrates that results depend on viewing perspective, i.e., on whether a total 1-h training session or an isolated WOD is considered. Thus, the evaluation again depends on whether isolated metabolic conditioning workouts are referred to as CrossFit® training or whether the entire training concept of CrossFit® is considered. By viewing solely the cardiovascular demands of the B-part (consisting of the WOD) in the present outcomes, the conclusion obtained is that the values were in line with the responses known so far in the literature and the pilot study (62). However, according to the guideline provided by the CrossFit® brand, a workout can only be described as CrossFit®, if the requirements for using the term, as in this thesis, are met. Thus, scientists and further research should overcome the terminological inequalities and develop a unified term to describe research on this type of training in the future, such as the term FFT preferred by Dominski et al. (17). Additionally, reasonable distinction and accurate reporting of the training methods studied are required. In this manner, physiological assessments enable coaches, athletes, and sports scientists to develop and implement effective training interventions and to recommend evidence-based practical applications (28).

Furthermore, the identification of optimal training methods requires the establishment of important performance parameters for CrossFit® athletes. By using the data from the online survey and comparing thousands of data available online, a response is provided regarding the nature of the performance profile and what regional differences may exist. The determination of a wide-ranging performance profile of American and German CrossFit® athletes allows the assessment of proficiency and sport-specific progress, the set-up of realistic training goals, and the identification of specific deficiencies. Athletes and coaches may use normative values to rank performance parameters internationally, compare individual athletes, and predict specific variables. By comparison of thousand of online available data, the Benchmark performance profile may be additionally useful for standard inclusion and exclusion criteria for future research, see **chapter 7**. Nevertheless, evidence-based data are scarce, and no consensus exists on which parameters predict specific CrossFit® performance optimal in training or competing settings. Regardless, in conjunction with previous indications (126, 133), the results suggest the dominant role of back squat performance and imply that building a strong lower body strength is beneficial for 'unknown and unknowable' challenges. Considering that the goal of the 'CrossFit® Games' is to test fitness across a broad range of motion modalities by annually changing tasks, research on what factors influence performance in this unfamiliar fitness test is still challenging in the future.

However, while training the 'unknown and unknowable', the greatest unpredictable challenge of this time occurred just around the world and therefore may also affect every CrossFit® athlete (154, 155). Therefore, the presented data on purchasing behavior and use of digital sports offers by CrossFit® and weightlifting athletes provide for the first time a detailed insight into how the athletes dealt during the first SARS-CoV-2 lockdown in Germany. Special mention deserves the finding that despite the massive restrictions, the CrossFit® athletes be able to continue their training and may in part be able to enhance health aspects by improving their body composition, see **chapter 8**. In analyzing the data from this study, it was also evident that practicing CrossFit® at an affiliated training center entails more than just the combination of resistance training and endurance as known from concurrent training. The appearance of the CF5 group, composed of athletes who have lost 5 kg of body mass or more and tend to train to improve their health, suggests that the social environment created in CrossFit® plays a crucial role. In this context, the use of online social networks by CrossFit® affiliates might influence the observed results. However, compared to the weightlifting athletes, the use of online sports increased more among the CrossFit® athletes, which seems to be a positive relation with more physical activity during the lockdown period. In this regard, short workouts with lower space requirements and reduced equipment, as shown in the pilot study, may be advantageous for training at home. In this way, the benefits of staying physically fit during lockdown or quarantine times should be mentioned. In accordance with the results of Gil et al., showing that physical strength allows a better recovery from a COVID-19 infection (173), maintaining CrossFit® training also during challenging times may be recommended. So, being physically active also has substantial effects on emotional well-being (174). Still, data and evidence on the impact of CrossFit® training on mental health during the pandemic times are limited. Since current evidence suggests that several mental health problems are associated with the COVID-19 pandemic (175), future research should also emphasize on psychological aspects of CrossFit® and its potential positive effect on health-related outcomes, especially during challenging times. The fact that CrossFit® managed to become a fast-growing fitness trend despite challenging times highlights the importance of further research in this area. So, on this day finding a CrossFit® training center for a try-out training session is easier than finding a Dunkin store for a doughnut (12, 15). This fact underlines the self-interest in maintaining healthy habits and the growing number of healthy lifestyle consumers, especially among younger people (176, 177). Thereby, the reasons for the high adherence to CrossFit® training and the associated consequences for public health are of particular interest in the future. As the results show the maintenance of CrossFit® training and usage of digital sport offers occurred across all age groups during the SARS-CoV-2 lockdown, the training concept may also have potential relevance for disease prevention and staying fit in old age.

Taken together, the investigations provide new insights into the physiological parameters of CrossFit® training, performance parameters, and the training behavior of CrossFit® athletes, offering an initial starting point for prospective, controlled, long-term, intervention studies. Based on the obtained outcomes regarding the simultaneous training of beginning and experienced CrossFit® athletes and the participation at online sport offers, T. Brandt and colleagues were able to investigate whether CrossFit® training improves mobility, strength, back issues, and well-being in inactive individuals with sedentary jobs in the Bundeswehr (40). Within 6 months, the training group observed significant improvements in specific areas as back pain decreased and strength and mobility increased. This effect persisted, and after 12 months, even though only digital training was provided at certain times due to the COVID-19 pandemic, participants achieved the physical ability to perform coordinately demanding movements at high intensity in a health-preserving manner (178). As well, this study also supports that CrossFit® allows young soldiers to train alongside injured veterans or civilian employees (advanced age to retirement) while achieving individual adaptations. As a result, this follow-up study confirms the assumption that CrossFit® claims to be a health-promoting training concept for everyone.

In conclusion, the objective of the training concept CrossFit® intends to prepare athletes best for 'unknown and unknowable' challenges, and how to face them in competition as well as in training or in everyday life. Identifying optimal procedures for building a comprehensive fitness and mindset remains an essential challenge for science regarding this novel type of training program. Nevertheless, as Charles Darwin theorized the principles of biology 150 years ago, the rationale of the 'Survival of the Fittest' may provide an advantage for any emerging and unpredictable future challenges, well beyond the fields of athletic performance (179, 180). In this respect, the CrossFit®-transference noted in the CrossFit®'s literature, describing a process enabling the athletes to channel their drive and motivation to get through a WOD, into their lives outside the training center, may motivate more scientists to examine how the culture of CrossFit® affects life and survival (181). With being fit and prepared for 'unknown and unknowable' challenges relying on the foundation of survival for military, police, and firefighters, the relevance of analyzing CrossFit® remains unchanged. Establishing a high level of functional physical fitness is still a critical prerequisite for the successful completion of military missions and is a matter of life and death in the worst-case scenario. In summary, CrossFit® is in many ways a characteristic sport that still requires further research on what way the 'Fittest on Earth®' arise.

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Appendix

Certain data included in the following table are derived from *CrossFit*®. © Copyright CrossFit®, LLC 2022. All Rights Reserved.

Table 4. Descriptions of the 'CrossFit® Open' workouts of the years 2016-2020 (72).

Workout	Score	Description
16.1	Repetitions completed	**20 min AMRAP of** 25-ft. overhead walking lunge (95/65 lb.) 8 burpees 25-ft. overhead walking lunge (95/65 lb.) 8 chest-to-bar pull-ups
16.2	TTC or repetitions completed in 20 min	**Beginning on a 4-min clock, complete AMRAP of** 25 toes-to-bars 50 double-unders 15 squat cleans (135/85 lb.) **If completed before 4 min, add 4 min to the clock and proceed to** 25 toes-to-bars 50 double-unders 13 squat cleans (185/115 lb.) **If completed before 8 min, add 4 min to the clock and proceed to** 25 toes-to-bars 50 double-unders 11 squat cleans (225/145 lb.) **If completed before 12 min, add 4 min to the clock and proceed to** 25 toes-to-bars 50 double-unders 9 squat cleans (275/175 lb.) **If completed before 16 min, add 4 min to the clock and proceed to** 25 toes-to-bars 50 double-unders 7 squat cleans (315/205 lb.)
16.3	Repetitions completed	**7 min AMRAP of** 10 power snatches (75/55 lb.) 3 bar muscle-ups
16.4	Repetitions completed	**13 min AMRAP of** 55 deadlifts (225/155 lb.) 55 wall-ball shots (20/14-lb. ball to 10/9-ft. target) 55-calorie row 55 handstand push-ups
16.5	TTC	**21-18-15-12-9-6-3 repetitions FT of** thrusters (95/65 lb.) burpees
17.1	TTC or repetitions completed in 20 min	**FT of** 10 dumbbell snatches (50/35 lb.) 15 burpee box jump-overs (24/20-inch) 20 dumbbell snatches (50/35 lb.) 15 burpee box jump-overs (24/20-inch) 30 dumbbell snatches (50/35 lb.) 15 burpee box jump-overs (24/20-inch) 40 dumbbell snatches (50/35 lb.) 15 burpee box jump-overs (24/20-inch) 50 dumbbell snatches (50/35 lb.) 15 burpee box jump-overs (24/20-inch)
17.2	Repetitions completed	**12 min AMRAP of alternating 2 rounds of** 50-ft. weighted walking lunge (50/35 lb.) 16 toes-to-bars 8 power cleans (50/35 lb.) **Then, 2 rounds of** 50-ft. weighted walking lunge (50/35 lb.) 16 bar muscle-ups 8 power cleans (50/35 lb.)

Table 4. (continued).

17.3	TTC or repetitions completed	**Prior to 8:00, complete 3 rounds of** 6 chest-to-bar pull-ups 6 squat snatches (95/65 lb.) **Then, 3 rounds of** 7 chest-to-bar pull-ups 5 squat snatches (135/95 lb.) ***Prior to 12:00, complete 3 rounds of** 8 chest-to-bar pull-ups 4 squat snatches (185/135 lb.) ***Prior to 16:00, complete 3 rounds of** 9 chest-to-bar pull-ups 3 squat snatches (225/155 lb.) ***Prior to 20:00, complete 3 rounds of** 10 chest-to-bar pull-ups 2 squat snatches (245/175 lb.) **Prior to 24:00, complete 3 rounds of** 11 chest-to-bar pull-ups 1 squat snatch (265/185 lb.) *If all repetitions are completed, time cap extends by 4 min.
17.4	Repetitions completed	**13 min AMRAP of** 55 deadlifts (225/155 lb.) 55 wall-ball shots (20/14-lb. ball to 10/9-ft. target) 55-calorie row 55 handstand push-ups
17.5	TTC	**10 rounds FT of** 9 thrusters (95/65 lb.) 35 double-unders
18.1	Repetitions completed	**20 min AMRAP of** 8 toes-to-bar 10 dumbbell hang clean and jerks (50/35 lb.) 14-calorie row
18.2 18.2a	TTC or repetitions completed in 12 min	**1-2-3-4-5-6-7-8-9-10 repetitions FT of** dumbbell squats (50/35 lb.) bar-facing burpees 1-rep-max clean Time cap: 12 minutes to complete 18.2 and 18.2a
18.3	TTC or repetitions completed in 14 min	**FT 2 rounds of** 100 double-unders 20 overhead squats (115/80 lb.) 100 double-unders 12 ring muscle-ups 100 double-unders 20 dumbbell snatches (50/35 lb.) 100 double-unders 12 bar muscle-ups
18.4	TTC or repetitions completed in 9 min	**FT of** 21 deadlifts (225/155 lb.) 21 handstand push-ups 15 deadlifts, (225/155 lb.) 15 handstand push-ups 9 deadlifts, (225/155 lb.) 9 handstand push-ups 21 deadlifts, (315/205 lb.) 50-ft. handstand walk 15 deadlifts, (315/205 lb.) 50-ft. handstand walk 9 deadlifts, (315/205 lb.) 50-ft. handstand walk
18.5	Repetitions completed	**7 min AMRAP of** 3 thrusters (100/65 lb.) 3 chest-to-bar pull-ups 6 thrusters (100/65 lb.) 6 chest-to-bar pull-ups 9 thrusters (100/65 lb.) 9 chest-to-bar pull-ups 12 thrusters (100/65 lb.) 12 chest-to-bar pull-ups 15 thrusters (100/65 lb.) 15 chest-to-bar pull-ups 18 thrusters (100/65 lb.) 18 chest-to-bar pull-ups This is a timed workout. If you complete the round of 18, go on to 21. If you complete 21, go on to 24, etc.

Table 4. (continued).

19.1	Repetitions completed	**15 min AMRAP of** 19 wall-ball shots (20/14-lb. ball to 10/9-ft. target) 19-cal. row
19.2	TTC or repetitions completed in 20 min	**Beginning on an 8-min clock, complete AMRAP of** 25 toes-to-bars 50 double-unders 15 squat cleans (135/85 lb.) 25 toes-to-bars 50 double-unders 13 squat cleans, (185/115 lb.) **If completed before 8 min, add 4 min to the clock and proceed to:** 25 toes-to-bars 50 double-unders 11 squat cleans, (225/145 lb.) **If completed before 12 min, add 4 min to the clock and proceed to:** 25 toes-to-bars 50 double-unders 9 squat cleans, (275/175 lb.) **If completed before 16 min, add 4 min to the clock and proceed to:** 25 toes-to-bars 50 double-unders 7 squat cleans, (315/205 lb.)
19.3	TTC or repetitions completed in 10 min	**FT of** 200-ft. dumbbell overhead lunge (50/35 lb.) 50 dumbbell box step-ups (24/20-inch) 50 strict handstand push-ups 200-ft. handstand walk
19.4	TTC or repetitions completed in 12 min	**FT 3 rounds of** 10 snatches (95/65 lb.) 12 bar-facing burpees **Then, rest 3 minutes before continuing with 3 rounds of** 10 bar muscle-ups 12 bar-facing burpees
19.5	TTC or repetitions completed in 20 min	**33-27-21-15-9 repetitions FT of** thrusters (95/65 lb.) chest-to-bar pull-ups
20.1	TTC or repetitions completed in 15 min	**10 rounds FT of** 8 ground to overhead (95/65 lb.) 10 bar-facing burpees
20.2	Repetitions completed	**20 min AMRAP** 4 dumbbell thrusters (50/35 lb.) 6 toes-to-bar 24 double-unders
20.3	TTC or repetitions completed in 9 min	**FT of** 21 deadlifts (225 lb/155 lb) 21 handstand push-ups 15 deadlifts, (225 lb/155 lb) 15 handstand push-ups 9 deadlifts, (225 lb/155 lb) 9 handstand push-ups 21 deadlifts, (315 lb/205 lb) 50-ft. handstand walk 15 deadlifts, (315 lb/205 lb). 50-ft. handstand walk 9 deadlifts, (315 lb/205 lb). 50-ft. handstand walk
20.4	TTC or repetitions completed in 20 min	**FT** 30 box jumps (24/20-inch) 15 clean and jerks (95/65 lb.) 30 box jumps (24/20-inch) 15 clean and jerks (135/85 lb.) 30 box jumps (24/20-inch) 10 clean and jerks (185/115 lb.) 30 single-leg squats 10 clean and jerks (225/145 lb.) 30 single-leg squats 5 clean and jerks (275/175 lb.) 30 single-leg squats 5 clean and jerks (315/205 lb.)

Table 4. (continued).

20.5	TTC or repetitions completed in 20 min	**20 min to complete the following work in any order** 40 muscle-ups 80-calorie row 120 wall ball shots (20/14-lb. ball to 10/9-ft. target)

Note. Weights are given in brackets, separated by gender (male/female). As many rounds or repetitions as possible (AMRAP); For time (FT); Repetitions (Reps). Time-to-completion (TTC).