

Research article

Cardiometabolic and Muscular Fatigue Responses to Different CrossFit® Workouts

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Abstract

CrossFit® consists of workouts of the day (WODs) in which different exercises are conducted at high intensity with minimal or no rest periods. This study sought to quantify exercise intensity and muscular fatigue in the three CrossFit® session modalities: gymnastics (G), metabolic conditioning (M) and weightlifting (W). Thirty two, young, strength-trained, healthy men completed the three WODs: G ("Cindy"), M (double skip rope jumps) and W (power cleans). The variables measured in the sessions were: mean heart rate (HR), rate of perceived exertion (RPE), blood lactate [lactate], and jump height (H), average power (AP) and maximum take-off velocity (V_{max}) in a counter movement jump test. In all three WODs, elevated HR values ($\geq 90\%$ of the theoretical HR_{max}) were recorded at the time points mid-session and end-session. Mean RPEs were 17.6 ± 1.6 (G WOD), 16.0 ± 2.3 (M WOD), and 15.7 ± 2.0 (W WOD). Postexercise [lactate] was higher than $10 \text{ mmol} \cdot \text{L}^{-1}$ for the three WODs. Following the G ("Cindy") and W (power cleans) WODs, respectively, significant muscular power losses were observed in H (7.3% and 8.1%), V_{max} (13.8% and 3.3%), AP relative (4.6% and 8.3%) and AP total (4.2% and 8.2%) while losses in the M WOD were not significant ($p > 0.05$). A vigorous intensity of exercise was noted in all three WODs, with greater mean HRs detected in the "Cindy" and skip rope WODs than power clean WOD. Muscular fatigue was produced in response to the "Cindy" and power clean WODs but not the skip rope WOD.

Key words: Heart rate, cardiovascular responses, countermovement test, high intensity interval training, blood lactate, muscle fatigue.

Introduction

CrossFit® is a relatively new sport's modality of training and competition that has recently exponentially expanded worldwide. Its exercises cover many movement patterns and are conducted at high intensity (Glasmann, 2007). Training is organized as daily sessions called "workouts of the day" or WODs. These WODs are executed with short or no rest periods, and combine exercises and movements in the form of a circuit (Glasmann, 2007). The objective of some of these exercises is to achieve the best time possible, while for others the goal is to complete as many rounds as possible over periods of 10 to 20 minutes (Smith et al., 2013). According to the contents of the WOD, there are three session modalities: gymnastics (G), in which the work involves the body itself (pull-ups, rope climb, push-ups, ring row exercises, air squats, burpees, etc.); metabolic

conditioning (M), including cardiovascular exercises such as running, rowing, or skip rope; and finally weightlifting (W), consisting of Olympic lifts (snatch, clean and jerk), deadlifts, squats, or overhead press lifts using, for example, kettlebells, sandbags, or medballs (Maté-Muñoz et al., 2017). Thus, although the different CrossFit® sessions vary widely in their exercises and movement patterns, they share the feature that training is performed at high intensity with little or no rest periods. However, the workloads used in each exercise are not controlled and preestablished workloads can be excessive for some individuals (Weinenthal et al., 2014). Further, few studies have examined physiological responses to these WODs. In a recent study, Fernández-Fernández et al. (2015) determined in a group of subjects with CrossFit® experience, acute physiological responses (VO_2 , oxygen consumption; HR, heart rate, [lactate], blood lactate concentration and RPE, rate of perceived exertion) to a W and G type WOD known respectively as "Fran" (thrusters + pull ups) and "Cindy" (pull-ups, push-ups, air squats). According to these responses, both WODs were described as high intensity ($HR_{mean} = 90\text{--}95\% HR_{max}$; [lactate] $> 14 \text{ mmol} \cdot \text{L}^{-1}$; RPE > 8). When cardioresponses to the "Cindy" WOD were examined in another study in participants with little experience with CrossFit® (Kliszczewicz et al., 2014), $HR_{mean} = 91 \pm 4.2\% HR_{max}$, a rate equivalent to vigorous exercise according to the American College of Sports Medicine (ACSM) (Garber et al., 2011), and $VO_2 = 63.8 \pm 12.3\% VO_{2max}$, also considered to indicate vigorous exercise (Kliszczewicz et al., 2014). Butcher et al., (2015) examined HR and RPE responses to two G type WODs. One included rest intervals (total 21 min of exercise, 6 sets of 60 s of 8 bench press + 10 kipping pull-ups or ring rows and box jumps for the remainder of the 60 s, and 3 min of rest) and the other WOD was 20 min of "Cindy" without rest. Results indicated that although both WODs gave rise to high HRs and similar RPEs, significant differences were produced in HR_{mean} (87.6 ± 5.6 for Cindy vs. $76.4 \pm 7.3\% HR_{max}$, $P = 0.01$).

Hence, although CrossFit® sessions can vary widely, very few work intensities have been quantified for the different WODs, with "Cindy" being the most widely analyzed.

Quantifying the intensity of exercise of different CrossFit® sessions will provide information about adequate training loads. As the training load has been linked to a risk of injury and/or disease (Drew and Finch, 2016), prescribing adequate training loads will lead to beneficial

physical and physiological adaptations, reducing the risks of injury and thus increasing the probability of competition success (Fox et al., 2018).

Only one study has compared CrossFit® WODs with and without rest intervals. In a recent study by Maté-Muñoz et al. (2017), it was noted that high intensity exercise without intervals, like the "Cindy" WOD or 5 min of power cleans, generated muscular fatigue, whereas muscular fatigue produced in response to a high-intensity interval exercise (double skip rope jumps), disappeared after 3 min of rest.

Muscular fatigue has been defined as any exercise-induced reduction in the maximal voluntary force or power produced by a muscle or muscle group (Bigland-Ritchie and Woods, 1984; Gandevia, 2001). This fatigue has a significant negative impact on performance (Meeusen et al., 2013) and has been related to a risk of injury due to biomechanical modification of the movement (Weisenthal et al., 2014). Hence, it is essential to quantify the muscular fatigue and intensity of Crossfit® WODs for training prescription and to elicit optimal adaptations, reducing the risk of injury.

Accordingly, the objectives of this study were: 1) to quantify the intensity of exercise and measure muscular fatigue during 3 CrossFit® WODs involving different movement patterns with varying work volumes and rest periods, and 2) to compare the different physiological and mechanical responses to the 3 WODs.

Methods

Experimental approach to the problem

To compare exercise intensity and muscular fatigue across the three different CrossFit® modalities, 4 exercise sessions were completed in 4 consecutive weeks in the order: Session 1 – WOD 1 or G WOD, consisting of "Cindy"; Session 2 – WOD 2 or M WOD, consisting of double skip rope jumps; Session 3 – incremental power clean test (Olympic lifts) to calculate the maximum lifting strength of the individual; and Session 4 – WOD 3 or W WOD, consisting of power cleans.

All sessions were completed on the same week day within the same three hour time window. The rest period between each session was one week. Ambient conditions for all sessions were the same (temperature: 21–25°C, atmospheric pressure: 715–730 mm Hg, and relative humidity: 40–50%). Exercises were executed in the CrossFit® Box of the Universidad de Alfonso X El Sabio, Madrid, Spain (see Figure 1 for experimental design).

Subjects

The subjects selected for this study were 32 healthy men who were students of the degree course in Physical activity and Sport Sciences. Mean participant age was 21.75 ± 2.54 years, weight 76.85 ± 7.26 kg, height 1.79 ± 0.06 m and body mass index (BMI) $23.99 \pm 1.70 \text{ kg} \cdot \text{m}^{-2}$. Participants' experience was more than 6 months of strength training, including free weight and Olympic lifts in their training routines. No subject consumed any type of medication or performance-enhancing drugs during the study. Further exclusion criteria were cardiovascular, metabolic, neurologic, or lung disease, or any orthopedic condition that could limit performance of the exercises. None of the participants had experience with CrossFit® WODs. Elite athletes were also excluded. In the 48 hours before each exercise session, it was required that subjects refrained from physical exercise, smoking or the intake of caffeine or alcohol.

After receiving an explanation of the nature of the study, written informed consent was obtained from each participant. The study design was in line with the tenets of the Declaration of Helsinki and received approval from the ethics committee of the University.

Exercise sessions

Power clean incremental load test: One week before WOD 3 (W type), an incremental load power clean test was conducted to determine each individual's maximum strength or 1RM. This test has been described in detail elsewhere (Maté-Muñoz et al., 2017). One week before the study onset, the subjects practiced the power clean with the help of a qualified weightlifting trainer (Figure 1).

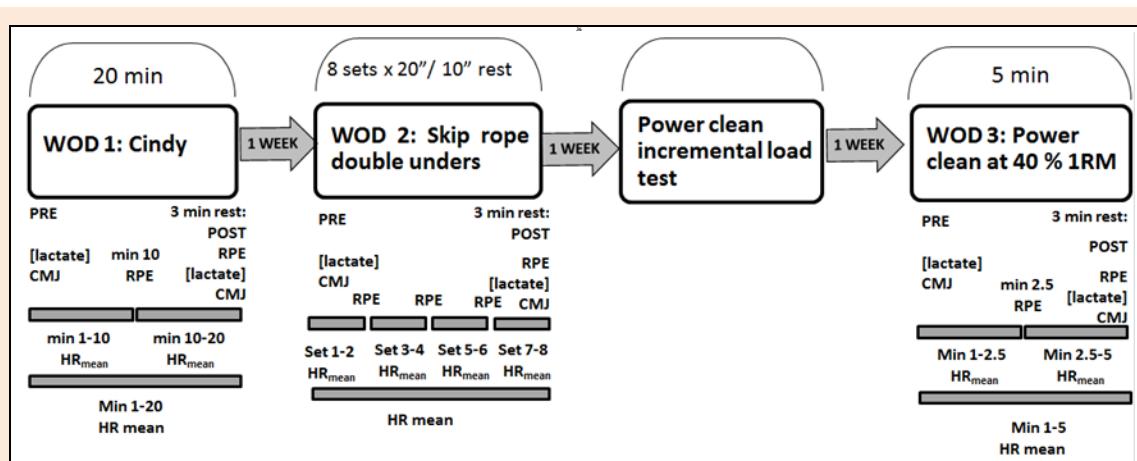


Figure 1. Experimental design. The 3 modalities of CrossFit® WODs examined in this study were: Gymnastics (Cindy), Metabolic conditioning (Crossfit® skip rope double-unders) and Weightlifting (power cleans). The figure shows the work/rest times and the time points in each WOD for the [lactate], heart rate, rate of perceived exertion and countermovement jump (CMJ) determinations.

Warm up: Before each WOD or the incremental test, a warm-up was performed consisting of 5 min of low intensity running followed by 5 min of joint mobility and dynamic stretching exercises.

WOD 1 (G): “Cindy” The gymnastics WOD was the “Cindy” workout (Kliszczewicz et al., 2014, Kliszczewicz et al., 2015). This WOD consists of as many rounds possible of 5 pull-ups, 10 push-ups and 15 air squats in 20 min. Each round had to be properly executed according to preestablished minimum standards to continue onto the next round. One of the authors was responsible for counting rounds using a hand held counter. The techniques used for each exercise have been described in detail elsewhere (Maté-Muñoz et al., 2017). For the pull-ups, butterfly or kipping variations were avoided as the subjects did not have sufficient experience with these movements (Figure 1).

WOD 2 (M): CrossFit® skip rope double unders The metabolic conditioning WOD consisted of double skip rope jumps (CrossFit® double unders) conducted as high-intensity interval training (HIIT). For the intermittent training protocol (Tabata et al., 1996), subjects completed as many double unders as possible in 8 sets of 20 s with 10 s of rest between sets. Test duration was 4 minutes. The number of double unders completed per set was counted by an observer while another observer guided the time periods of work and rest (Figure 1).

WOD 3 (W): power cleans The weight lifting WOD consisted of the maximum number of power cleans possible in 5 min lifting a load equivalent to 40% of the individual's 1RM determined 1 week previously. An observer counted the total number of power cleans completed (Figure 1).

Response measurements

Heart rate: Before each of the WOD sessions, subjects were fitted with a HR monitor (Polar RS-800CX; Polar Electro OY, Kempele, Finland). Heart rate data were stored and subsequently extracted using the software Polar Pro-Trainer 5. During each WOD, HR_{mean} values were recorded as follows: WOD 1, for the whole trial and for minutes 1-10 and 10-20; WOD 2, for the whole trial and for sets 1 and 2 (S2), 3 and 4 (S4), 5 and 6 (S6) and 7 and 8 (S8); and WOD 3 for the whole trial and for minutes 1-2.5 and 2.5-5 (Figure 1). The equation used to calculate HR_{max} for each participant, with which the HR data obtained for each WOD were compared, was 208 – 0.7 x age (Tanaka et al., 2001).

Blood lactate concentrations: Before warm-up and at the end of each WOD, a finger prick blood sample (5 µl) was obtained by a single operator to determine blood lactate concentrations [lactate] in a portable analyzer (Lactate Pro LT-1710, Arkray Factory Inc., KDK Corporation, Siga, Japan) validated for this purpose (McNaughton, et al., 2002; Mclean et al., 2004).

Perceived exertion: The rate of perceived exertion was recorded using a 6-20 Borg scale (Borg 1970) as ranging from very, very light to very, very heavy. RPEs at the levels cardiopulmonary, muscular and general were recorded in minute 10 and at the end of the trial (minute 20) in WOD 1, in minute 2.5 and at the end of the trial (minute

5) in WOD 2, and in S2, S4, S6 and S8 in WOD 3. To help the participants to differentiate between the different RPE levels, they were instructed to think about whether their feeling of exertion involved the heart and lungs (RPE cardiopulmonary), the muscles used in the exercise (RPE muscular), or if they had a feeling of general exertion affecting the heart, lungs and muscles (RPE general).

Muscular fatigue: Muscular fatigue in the legs was assessed by measuring vertical reaction forces (0-10 kN; sampling velocity 0.5 kHz) in a countermovement jump (CMJ) (Gorostiaga et al., 2010) on a portable, 92 x 92 x 12.5 cm force platform (Quattro Jump model 9290AD; Kistler Instruments, Winterthur, Switzerland) before and 3 minutes after completing each WOD. The jump was initiated while standing on the platform with legs extended and hands on hips. For the jump, the legs are first flexed to 90° (eccentric action) and then explosively extended in a coordinated manner (concentric action) aiming for maximum height. During the flight stage, the knees are extended. Contact with the ground is made with the toes first. During the test, subjects kept their hands on their hips and avoided sideways displacements during the flight stage.

At each established time point, participants undertook 3 jumps separated by 30 s so that mean values could be recorded for: jump height (H), maximum take-off velocity (V_{max}) average power relative (APR), and average power total (APT). All variables were calculated using vertical ground reaction force (GRF) data obtained using a force platform. The vertical component of center of mass (COM) velocity was estimated using the impulse method (Linthorne, 2001). Net impulse was obtained by integrating the GRF from 2 seconds before the first movement of the participant (Street et al., 2001) using the trapezoid method. Subsequently, the vertical velocity of COM was calculated by dividing the net impulse by the participant's body mass (Floría et al., 2016). V_{max} ($m \cdot s^{-1}$) was taken as the maximum velocity attained at the end of the concentric phase of the jump, just before take-off. H (cm) was defined as the maximum distance covered by the participant during a vertical jump calculated by double integration of the force. In other words it was calculated from V_{max} of the COM just before take-off, and considering the deceleration effect of gravity [$(V_{max})^2/2 \times 9.81$], where V_{max} is the maximum velocity just before take-off and 9.81 is acceleration due to gravity. Power was determined from the unfiltered force-time history using the impulse momentum principle (Owen et al., 2014). ART ($watts \cdot kg^{-1}$) was calculated as the product of the average velocity and vertical component of the GRF of the whole jump in relation to a kg of body mass (GRF x COM velocity). APT (watts) was the average power recorded for the total body weight of each individual.

GRF measurements can help identify symptoms of muscular fatigue arising from the reduced production of force (Ortega et al., 2010; Barker et al., 2018). These variables were selected on the grounds that jump height and power losses during an exercise session have been defined as indicators of mechanical and neuromuscular fatigue (Sánchez-Medina and González-Badillo, 2011) due to decreased muscle control, coordination, and force-generating capacity after fatigue (Cooper et al., 2018). An increased

curvature of the force–velocity relationship could mainly indicate a loss of power thus delaying the contractile properties of skeletal muscle as one of the characteristic features of fatigue (Jones, 2010).

Statistical analysis

The normal distribution of the data was first checked using the Shapiro-Wilk test. Relationships between the cardiometabolic variables (HR and [lactate]) and RPE were established through Pearson's correlation and linear regression. To compare data reflecting intensity of exercise (HR, [lactate], RPE) across the different CrossFit® WODs, we used one-factor ANOVA, after first checking for homogeneity of variance using Levene statistics. In cases of non homogeneous variance ($p < 0.05$), a non-parametric ANOVA was performed (Kruskall-Wallis).

To quantify muscular fatigue pre-post exercise in the different WODs, a Student *t*-test for paired samples was used. Percentage improvements in the CMJ test were calculated using the equation [post - pre]/pre X 100. Linear regression was used to assess correlations between [lactate] and the jump height and power variables.

Also, to compare the effects of metabolic and muscular fatigue among the three WODs, we used a with repeated measures two-way analysis of variance, once we had confirmed the homogeneous variances of the initial variables through Levene statistics. That is, we considered an inter-subject factor, or *Group* effect (3 levels: WOD 1, WOD 2, WOD 3) and an intra-subject factor, or *Time* effect (2 levels: preexercise, postexercise) as well as the effect of the interaction general linear model between the two. When significant differences were observed in the interaction Group x Time ($p < 0.05$), one-way ANOVAs with post-hoc Bonferroni correction were performed to compare differences among the sessions (WOD 1, WOD 2, WOD 3).

All data are provided as their means (M) and standard deviations (*SD*) and $\pm 95\%$ confidence intervals (CI). In general linear model, effect size (*ES*) and statistical power (*SP*) were calculated. Significance was set at $p < 0.05$. All statistical tests were performed using the software package SPSS version 20.0 (SPSS, Chicago, III).

Results

The results recorded for the three CrossFit® WODs ("Cindy" rounds in WOD 1, double unders in each set of WOD 2 and power cleans executed in the 5 minutes' duration of WOD 3) are provided in Table 1.

Maximum heart rate: In Table 2 we provide the HR_{max} values recorded in the three WODs in relation to theoretical maximum HR values (Tanaka et al., 2001). These data indicate elevated HR recorded both at the mid-session and end-session time points in all three WODs. With the exception of the HR_{mean} observed in WOD 3 (~89%), all HRs were 90% of the theoretical HR_{max}, indicating the high cardiovascular demands of the three types of exercise.

The RPEs recorded at the end of the exercise sessions are provided in Table 3 for each WOD.

Table 1. Results recorded in the three CrossFit® WODs. Data are means \pm SD.

Variables	Skip rope double unders
Rounds (n)	14.00 \pm 7.90
Double unders: Set 1 (n)	14.00 \pm 7.90
Set 2 (n)	12.90 \pm 7.38
Set 3 (n)	12.00 \pm 6.54
Set 4 (n)	9.87 \pm 4.98
Set 5 (n)	10.90 \pm 5.78
Set 6 (n)	10.09 \pm 5.08
Set 7 (n)	10.46 \pm 5.26
Set 8 (n)	9.53 \pm 5.13
Power cleans (n)	109.37 \pm 24.83
"Cindy"	23.53 \pm 3.88

Table 2. Descriptive statistics for HR recorded in the WODs in relation to theoretical HR_{max} (Tanaka et al. 2001).

WOD 1 (Cindy)	Mean \pm SD
HR _{max} theoretical (bpm)	193 \pm 2
HR Min 10 (bpm)	184 \pm 10
% HR _{max} theoretical Min 10	95 \pm 5
HR Min 20 (bpm)	187 \pm 9
% HR _{max} theoretical Min 20	97 \pm 5
HR _{mean} (bpm)	178 \pm 9
% HR _{max} theoretical average	92 \pm 5
WOD 2 (skip rope double unders)	
HR _{max} theoretical (bpm)	193 \pm 2
HR S2 (bpm)	177 \pm 11
% HR _{max} theoretical S2	92 \pm 2
HR S4 (bpm)	182 \pm 9
% HR _{max} theoretical S4	94 \pm 5
HR S6 (bpm)	183 \pm 8
% HR _{max} theoretical S6	95 \pm 4
HR S8 (bpm)	183 \pm 8
% HR _{max} theoretical S8	95 \pm 4
HR _{mean} (bpm)	178 \pm 9
% HR _{max} theoretical average	92 \pm 5
WOD 3 (power cleans)	
HR _{max} theoretical (bpm)	193 \pm 2
HR Min 2.5 (bpm)	178 \pm 11
% HR _{max} theoretical Min 2.5	92 \pm 6
HR Min 5 (bpm)	185 \pm 10
% HR _{max} theoretical Min 5	96 \pm 5
HR _{mean} (bpm)	171 \pm 11
% HR _{max} theoretical average	89 \pm 6

HR_{max} = maximum heart rate; bpm = beats per minute; % = percentage; S2 = set 2; S4 = set 4; S6 = set 6; S8 = set 8; WOD 1 = G modality CrossFit® Workout of the Day ("Cindy"); WOD 2 = M modality CrossFit® Workout of the Day (skip rope double unders); WOD 3 = W modality CrossFit® Workout of the Day (power cleans).

Table 3. Descriptive statistics for RPEs recorded at the end of the three WODs. Data are means \pm SD.

WOD 1	RPE Muscular	16.96 \pm 1.97
WOD 2	RPE Cardio	17.09 \pm 1.69
WOD 3	RPE General	17.62 \pm 1.60
WOD 1	RPE Muscular	15.68 \pm 2.91
WOD 2	RPE Cardio	16.12 \pm 2.18
WOD 3	RPE General	16.00 \pm 2.32
WOD 1	RPE Muscular	15.53 \pm 2.10
WOD 2	RPE Cardio	15.00 \pm 1.90
WOD 3	RPE General	15.65 \pm 2.02

RPE = rate of perceived exertion; n = numbers; WOD 1 = G modality CrossFit® workout of the day ("Cindy"); WOD 2 = M modality CrossFit® workout of the day (skip rope double unders); WOD 3 = W modality CrossFit® workout of the day (power cleans).

Heart rate, lactate, and rate of perceived exertion:

The correlations detected among the cardiometabolic factors and RPE were: 1) positive and strong correlation ($|r| > 0.70$) between [lactate] and HR across the three WODs (WOD 1 $r = 0.938$; $p < 0.01$; $R^2 = 0.880$ $p < 0.01$; WOD 2 $r = 0.915$; $p < 0.01$; $R^2 = 0.838$ $p < 0.01$; WOD 3 $r = 0.933$; $p < 0.01$; $R^2 = 0.870$ $P < 0.01$); 2) moderate correlation ($0.30 \leq |r| \leq 0.70$) between HR and RPE in WOD 2 (RPE muscular $r = 0.330$; $p < 0.01$; $R^2 = 0.109$; RPE cardio $r = 0.361$; $p < 0.01$; $R^2 = 0.130$; RPE general $r = 0.361$, $p < 0.01$; $R^2 = 0.130$); and 3) weak correlation ($|r| < 0.30$) between HR and RPE cardio in WOD 1 ($r=0.314$; $p < 0.011$, $R^2 = 0.099$). No correlation was observed between HR and RPE for WOD 3 (Table 4).

The different variables reflecting work intensity are compared across the WODs in Table 5. Thus, one-way ANOVA detected significant differences among WODs in HR_{mean} ($F = 4.839$, $p \leq 0.01$), final [lactate] ($F=3.557$ $p \leq$

0.05) and in RPE muscular ($F = 3.548$ $p \leq 0.033$), RPE cardio ($F = 9.38$ $p \leq 0.01$), and RPE general ($F = 8.782$ $p \leq 0.01$), while no differences were detected in final HR ($F=1.859$ $p > 0.05$). As no homogeneity of variance was observed for resting [lactate], the non-parametric Kruskall-Wallis was used, indicating significant differences between WOD 1 and WOD 3 ($p = 0.036$). Further, pairwise comparisons revealed significant differences in HR_{mean} between WOD 1 and WOD 3 ($p = 0.024$), and between WOD 2 and WOD 3 ($p = 0.026$). For final [lactate], differences were noted between WOD 1 and WOD 2 ($p = 0.032$). Finally, for the RPE scores obtained after exercise, significant differences were found between WODs 1 and 3 in RPE muscular ($p = 0.05$), RPE cardio ($p = 0.000$) and RPE general ($p = 0.001$). Further, RPE general differed significantly between WODs 1 and 2 ($p = 0.005$). No differences emerged in the remaining pairwise comparisons.

Table 4. Correlations detected between cardiometabolic factors and RPE used to indicate the work intensities of the three Crossfit® WODs.

		Pearson		Linear regression	
		<i>r</i>	<i>P</i>	<i>R</i> ²	<i>P</i>
WOD 1	[Lactate] (IF) VS. HR (IF)	0.938	0.000	0.880	0.000
	HR (Min10-Min20) VS. RPE M (Min10-Min20)	-0.091	0.473	0.008	0.473
	HR (Min10-Min20) VS. RPE C (Min10-Min20)	0.314	0.011	0.099	0.011
	HR (Min10-Min20) VS. RPE G (Min10-Min20)	0.155	0.221	0.024	0.221
WOD 2	[Lactate] (IF) VS. HR (IF)	0.915	0.000	0.838	0.000
	HR (S2-S4-S6-S8) VS. RPE M (S2-S4-S6-S8)	0.330	0.000	0.109	0.000
	HR (S2-S4-S6-S8) VS. RPE C (S2-S4-S6-S8)	0.361	0.000	0.130	0.000
	HR (S2-S4-S6-S8) VS. RPE G (S2-S4-S6-S8)	0.361	0.000	0.130	0.000
WOD 3	[Lactate] (IF) VS. HR (IF)	0.933	0.000	0.870	0.000
	HR (Min2.5-Min5) VS. RPE M (Min2.5- Min5)	-0.033	0.794	0.001	0.794
	HR (Min2.5- Min5) VS. RPE C (Min2.5-Min5)	0.103	0.419	0.011	0.419
	HR (Min2.5- Min5) VS. RPE G (Min2.5-Min5)	0.036	0.779	0.001	0.779

IF = Initial-Final; HR = Heart rate; RPE = Rate of perceived exertion; Min2.5 = minute 2.5; Min5 = minute 5; Min10 = minute 10; Min20 = minute 20; M = Muscular; C = Cardio; G = General; S2 = Set 2; S4 = Set 4; S6 = Set 6; S8 = Set 8; WOD 1 = G modality CrossFit® workout of the day ("Cindy"); WOD 2 = M modality CrossFit® workout of the day (skip rope double unders); WOD 3 = W modality CrossFit® workout of the day (power cleans).

Table 5. Comparing cardiometabolic variables and RPE among the three CrossFit® WODs.

Variable	WOD	M ± SD	CI (95%)	<i>P</i>
HR final (bpm)	1	187 ± 9	184 to 191	
	2	183 ± 8	180 to 186	0.161
	3	185 ± 10	181 to 188	
HR_{mean} (bpm)	1	178 ± 9§	175 to 182	
	2	178 ± 9	175 to 181	0.010 *
	3	171 ± 11	167 to 176	
[Lactate] rest (mmol·L⁻¹)	1	1.55 ± 0.61 §	1.33 to 1.76	
	2	1.30 ± 0.37	1.17 to 1.44	0.016†
	3	1.23 ± 0.32	1.12 to 1.35	
[Lactate] final (mmol·L⁻¹)	1	12.02 ± 2.12 ‡	11.25 to 12.79	
	2	10.37 ± 2.91	9.32 to 11.43	0.032 †
	3	11.49 ± 2.46	10.61 to 12.38	
RPE final Muscular	1	16.96 ± 1.97 §	16.26 to 17.68	
	2	15.68 ± 2.91	14.64 to 16.74	0.033†
	3	15.53 ± 2.10	14.77 to 16.29	
RPE final Cardio	1	17.09 ± 1.69 §	16.48 to 17.70	
	2	16.12 ± 2.18	15.34 to 16.91	0.000 *
	3	15.00 ± 1.90	14.31 to 15.69	
RPE final General	1	17.62 ± 1.60‡§	17.05 to 18.20	
	2	16.00 ± 2.32	15.16 to 16.84	0.000 *
	3	15.65 ± 2.02	14.93 to 16.39	

HR = heart rate; RPE = rate of perceived exertion; bpm = beats per minute; CI = confidence interval; WOD 1 = G modality CrossFit® workout of the day ("Cindy"); WOD 2 = M modality CrossFit® workout of the day (skip rope double unders); WOD 3 = W modality CrossFit® workout of the day (power cleans); * = significant difference between WODs; $p \leq 0.01$. † = significant differences between WODs; $p < 0.05$. ‡ = significant difference WOD 1 vs 2 ($p \leq 0.05$). § significant difference WOD 1 vs 3 ($p \leq 0.05$). ||, significant difference WODs 2 vs 3 ($p \leq 0.05$).

Table 6. Variables related to muscular and metabolic fatigue recorded in the three WODs.

Variables	WOD	Pre	Post	Effect Size	P Group effect	P Time effect	P Interaction Group x Time
Lactate] (mmol·L ⁻¹)	1	1.55 ± 0.61	12.02 ± 2.12	-5.046	0.017*	0.000*	0.063
	2	1.30 ± 0.37	10.37 ± 2.91	-3.022			
	3	1.23 ± 0.32	11.49 ± 2.59	-4.245			
H (cm)	1	37.99 ± 4.42	35.39 ± 4.69	1.094	0.381	0.000*	0.213
	2	37.05 ± 4.37	36.63 ± 4.66	0.288			
	3	36.57 ± 4.13	33.82 ± 4.97	1.050			
Vmax (m·s ⁻¹)	1	2.88 ± 0.15	2.53 ± 0.30	1.089	0.015*	0.000*	0.000*
	2	2.84 ± 0.15	2.81 ± 0.17	0.309			
	3	2.83 ± 0.13	2.74 ± 0.17	0.872			
APR (watts·kg ⁻¹)	1	32.23 ± 3.00	30.81 ± 4.13	0.552	0.078	0.000*	0.013*
	2	31.59 ± 3.36	30.96 ± 3.92	0.298			
	3	30.89 ± 3.31	28.53 ± 3.85	1.091			
APT (watts)	1	2463.48 ± 287.42	2364.85 ± 398.95	0.502	0.164	0.000*	0.011*
	2	2424.44 ± 299.49	2382.08 ± 375.99	0.282			
	3	2364.68 ± 305.99	2186.36 ± 315.76	0.958			

H = jump Height; Vmax = maximum takeoff velocity; APR = average power relative; APT = average power total. Pre = Preeexercise; Post = Postexercise; WOD 1 = G modality CrossFit® workout of the day ("Cindy"); WOD 2 = M modality CrossFit® workout of the day (skip rope double unders); WOD 3 = W modality CrossFit® workout of the day (power cleans). * Significant difference ($p < 0.05$).

Table 7. Correlations between muscular fatigue and blood lactate concentration in the three WODs.

			Linear regression	
			R ²	P
WOD 1	H (Pre-Post) VS. [lactate] (Pre- Post)		0.110	0.008*
	APR (Pre-Post) VS. [lactate] (Pre- Post)		0.090	0.016*
	APT (Pre-Post) VS. [lactate] (Pre- Post)		0.081	0.023*
WOD 2	H (Pre-Post) VS. [lactate] (Pre- Post)		0.141	0.002*
	APR (Pre-Post) VS. [lactate] (Pre- Post)		0.144	0.002*
	APT (Pre-Post) VS. [lactate] (Pre- Post)		0.179	0.000*
WOD 3	H (Pre-Post) VS. [lactate] (Pre- Post)		0.119	0.005*
	APR (Pre-Post) VS. [lactate] (Pre- Post)		0.167	0.001*
	APT (Pre-Post) VS. [lactate] (Pre- Post)		0.123	0.004*

H = jump height; [lactate] = blood lactate concentration APR = average power relative; APT = average power total; Pre = preeexercise; Post = postexercise; WOD 1 = G modality CrossFit® workout of the day ("Cindy"); WOD 2 = M modality CrossFit® workout of the day (skip rope double unders); WOD 3 = W modality CrossFit® workout of the day (power cleans). * Significant difference ($p < 0.05$).

Countermovement jump height and average power losses

WOD 1: The CMJ variables found to differ significantly pre-postexercise in this WOD were jump height (M = 2.597 cm, CI 95% = 1.742 – 3.452, $t = 6.195$; ES = 1.094, $p = 0.000$) (Table 6), and maximum take-off velocity (V_{max}), average power relative (APR) and average power total (APT) (M = 0.34 m·s⁻¹, CI 95% = 0.23 – 0.46, $t = 6.164$; ES = 1.089, $p = 0.000$, M = 1.42 watts·kg⁻¹, CI 95% = 0.49 – 2.35, $t = 3.127$; ES = 0.552, $p = 0.004$, and M = 98.62 watts, CI 95% = 27.95 – 169.30, $t = 2.846$; ES = 0.502, $p = 0.008$, respectively).

WOD 2: In this WOD, no pre-postexercise differences were observed in any of the jump ability variables (Table 6) (H: M = 0.42 cm, CI 95% = -0.10 – 0.93, $t = 1.631$; ES = 0.288, $p = 0.113$, V_{max}: M = 0.03 m·s⁻¹, CI 95% = -0.01 – -0.07, $t = 1.749$; ES = 0.309, $p = 0.090$, APR: M = 0.63 watts·kg⁻¹, CI 95% = -0.13 – 1.38, $t = 1.689$; ES = 0.298, $p = 0.101$, APT: M = 42.36 watts, CI 95% = -11.73 – 96.46, $t = 1.597$; ES = 0.282, $p = 0.120$).

WOD 3: In response to WOD 3, significant reductions were observed 3 minutes after exercise in all the jump ability variables examined (H: M = 2.76 cm, CI 95% = 1.81 – 3.70, $t = 5.948$; ES = 1.050, $p = 0.000$, V_{max}: M = 0.09

m·s⁻¹, CI 95% = 0.05 – 0.13, $t = 4.941$; ES = 0.872, $p = 0.000$, APR: M = 2.35 watts·kg⁻¹, CI 95% = 1.58 – 3.13, $t = 6.178$; ES = 1.091, $p = 0.000$, APT: M = 178.32 watts, CI 95% = 111.26 – 245.38, $t = 5.423$; ES = 0.958, $p = 0.000$) (Table 6).

Weak correlation was detected between the muscular fatigue indicators average power or jump height and [lactate] ($|R^2| < 0.30$) (Table 7).

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$= -0.01 - 0.07$, $t = 1.749$, $ES = 0.309$, $p = 0.090$, APR: $M = 0.63 \text{ watts} \cdot \text{kg}^{-1}$, CI 95% = $-0.13 - 1.38$, $t = 1.689$; $ES = 0.298$, $p = 0.101$, APT: $M = 42.36 \text{ watts}$, CI 95% = $-11.73 - 96.46$, $t = 1.597$; $ES = 0.282$, $p = 0.120$.

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Weak correlation was detected between the muscular fatigue indicators average power or jump height and [lactate] ($|R^2| < 0.30$) (Table 7).

Muscular fatigue and blood lactate concentrations

Significant pre-postexercise differences in [lactate] emerged among the three WODs (Table 6) ($F = 1485.347$; $p = 0.000$, $ES = 0.941$, $SP = 1.000$), and between WOD 1 and WOD 2 ($F = 3.995$; $p = 0.021$, $ES = 0.075$, $SP = 0.703$) ($p = 0.017$) after post hoc Bonferroni correction. In contrast, no significant effect on [lactate] was produced by the interaction Time x Group ($F = 2.852$; $p = 0.063$, $ES = 0.058$, $SP = 0.547$).

For the factor time, a significant loss in jump height was produced ($F = 57.049$; $p = 0.000$, $ES = 0.380$, $SP = 1.000$), without significant differences between groups, or WODs ($F = 0.975$; $p = 0.381$, $ES = 0.021$, $SP = 0.215$) nor Time x Group ($F = 1.573$; $p = 0.213$, $ES = 0.033$, $SP = 0.326$). For V_{\max} , significant differences were recorded in the factor time ($F = 57.632$; $p = 0.000$, $ES = 0.383$, $SP = 1.000$), Time x Group ($F = 22.032$; $p = 0.000$, $ES = 0.321$, $SP = 1.000$) and group ($F = 4.402$; $p = 0.015$, $ES = 0.086$, $SP = 0.746$). As differences were noted in the interaction Time x Group, we conducted a one-way ANOVA for the time point postexercise with Bonferroni post hoc correction to compare this variable among the different WODs. These data indicated that V_{\max} was significantly reduced in WOD 1 compared to WODs 2 and 3 ($p = 0.000$, $p = 0.001$ respectively).

The other variables related to muscular fatigue APR and APT showed significant reductions with the factor time ($F = 39.590$; $p = 0.000$, $ES = 0.299$, $SP = 1.000$ and ($F = 34.151$; $p = 0.000$, $ES = 0.269$, $SP = 1.000$, respectively), though differences among groups were not significant. In contrast, the interaction Time x Group did vary significantly for APR ($F = 4.582$; $p = 0.013$, $ES = 0.090$, $SP = 0.764$) and APT ($F = 4.690$; $p = 0.011$, $ES = 0.092$, $SP = 0.775$). A one-way ANOVA for the time point postexercise revealed a significant difference in APR between WODs 2 and 3 ($p = 0.049$).

Discussion

Given the wide variety of CrossFit® WODs employed, the objective of our study was to compare physiological and mechanical responses among WODs involving a high intensity of exercise but very different movement patterns. These WODs (designated here as 1, 2 and 3 respectively)

were the G modality "Cindy", which has been the focus of intense research, the M WOD consisting of CrossFit® skip rope double unders and rest periods (8 x 20 s/10 s rest), and the W WOD consisting of power cleans (5 min) without rest periods. Knowing the intensity of exercise and the muscular fatigue generated by the different Crossfit® WODs is useful for tailoring training loads to each individual. An adequate training load will induce beneficial adaptations and avoid injury or disease.

One of the findings of this study was the high intensity of exercise recorded in the three WODs which was measured in terms of cardiovascular variables, metabolic variables and of the subject's perceived exertion.

Heart rate: When we examined exercise intensity at the cardiovascular level, HRs at the end of WODs 1, 2 and 3 respectively were $187 \pm 10 \text{ bpm}$ ($97.2 \pm 4.8 \% \text{ HR}_{\max}$), $183 \pm 9 \text{ bpm}$ ($94.8 \pm 4.5 \% \text{ HR}_{\max}$), and $185 \pm 10 \text{ bpm}$ ($95.8 \pm 5.4 \% \text{ HR}_{\max}$), with HR_{mean} values recorded of $178 \pm 10 \text{ bpm}$ ($92.5 \pm 4.9 \% \text{ HR}_{\max}$) (WOD 1), $178 \pm 9 \text{ bpm}$ ($92.4 \pm 4.7 \% \text{ HR}_{\max}$) (WOD 2), and $172 \pm 12 \text{ bpm}$ ($89 \pm 6 \% \text{ HR}_{\max}$) (WOD 3). According to ACSM guidelines, these end-exercise HRs could be described as being close to that corresponding to maximum intensity exercise (Garber et al. 2011). However, if we consider the mean HR recorded throughout each session, this intensity of exercise would be considered vigorous and close to maximal (~90 % HR_{\max}) as the ASCM defines this intensity as being between 77 and 95% of HR_{\max} . Thus although no significant differences were detected in HR_{final} among the different WODs, we did note a significantly higher HR_{mean} for WODs 1 ("Cindy") and 2 (skip rope double unders) than for WOD 3 (power cleans). This difference might be explained by the specific movement pattern of the power clean, as it is a loaded strength exercise generating high power outputs with a large contribution of glycolytic energy metabolism.

This high cardiovascular requirement noted for "Cindy" is comparable to that described by others who have provided mean HRs for this CrossFit® WOD of $182 \pm 7 \text{ bpm}$ ($97.4 \pm 2.4 \% \text{ HR}_{\max}$) (Fernández-Fernández et al., 2015), $171 \pm 14 \text{ bpm}$ ($91 \pm 4.2 \% \text{ HR}_{\max}$) (Kliszczewicz et al., 2014), $88 \pm 6 \% \text{ HR}_{\max}$ (Butcher et al., 2015), and $93.3 \pm 1.2 \% - 97.7 \pm 1.9 \% \text{ HR}_{\max}$ (Kliszczewicz et al., 2015). We also obtained a similar HR_{mean} for our W or power clean WOD to the HR_{mean} obtained for "Fran" (also a W WOD) in the study by Fernández-Fernández et al., (2015) ($179 \pm 8 \text{ bpm}$; $95.4 \pm 3 \% \text{ HR}_{\max}$).

The two studies examining the "Cindy" workout that described similar HR_{\max} to ours, related HR_{\max} to $\text{VO}_{2\max}$ reporting values of around 66% $\text{VO}_{2\max}$ (Fernández-Fernández et al., 2015) and 64% $\text{VO}_{2\max}$ (Kliszczewicz et al., 2014). These proportions indicate a vigorous intensity of exercise (60%-85% $\text{VO}_{2\max}$) and are considered more effective than a moderate intensity of exercise (40%-60% $\text{VO}_{2\max}$) to improve $\text{VO}_{2\max}$ (Swain, 2005). In the present double skip rope jumps (WOD 2), the regimen was one of high intensity interval training (HIIT), which has also been reported to significantly improve $\text{VO}_{2\max}$ over continuous regimens (Kessler et al., 2012).

Rate of perceived exertion: Using the subjective RPE scale to measure exercise intensity, we obtained RPE-general scores of 17.6 ± 1.6 (WOD 1), 16.0 ± 2.3 (WOD

2), and 15.7 ± 2.0 (WOD 3), which were similar to the RPE-muscular and RPE-cardio recorded. RPEs were, however, significantly higher for “Cindy” (WOD 1) than the double under (WOD 2) and power clean (WOD 3) workouts. These rates are described in the exertion scale as *hard* or *very hard* (Borg, 1970). This means that our study participants had the feeling that the exercises executed were high intensity and this intensity is described by the ACSM as vigorous (RPE 14-17) (Garber et al., 2011). According to the findings of Alberton et al. (2013) in a study examining aerobic exercises of increasing intensity, our WODs 2 and 3 would be of an intensity around the second ventilatory threshold (VT_2), while WOD 1 (“Cindy”) would be above this VT_2 threshold, as they detected high correlation between the first ventilatory threshold (VT_1) and RPEs close to 12, and between VT_2 and RPEs of around 16 (Alberton et al., 2013).

Blood lactate: When exercise intensity in the CrossFit® sessions was quantified in terms of [lactate], this variable always exceeded $10 \text{ mmol} \cdot \text{L}^{-1}$ (WOD 1 12.0 ± 2.1 , WOD 2 10.4 ± 2.9 , WOD 3 11.5 ± 2.5), also indicating a high intensity of exercise and consistent with prior findings reported by Maté-Muñoz et al., (2017). However, significant differences in capillary blood lactate concentrations emerged between the “Cindy” WOD and the other two workouts. These differences could perhaps be attributable to different work volumes and to rest intervals in the skip rope WOD. In the study by Fernández-Fernández et al., (2015), higher [lactate] were reported for the “Cindy” workout ($14.5 \pm 3.2 \text{ mmol} \cdot \text{L}^{-1}$) than those detected here. This may be explained by the higher resting blood lactate levels of the participants of the Fernández-Fernández study ($4.0 \pm 1.3 \text{ mmol} \cdot \text{L}^{-1}$ VS. $1.6 \pm 0.6 \text{ mmol} \cdot \text{L}^{-1}$).

Exercise intensity in other sport modalities: Our data can also be compared with those obtained at the end of exercise in other sport modalities. For example, [lactate]_{final} levels of $13 \pm 1.5 \text{ mmol} \cdot \text{L}^{-1}$ and $10 \pm 2.9 \text{ mmol} \cdot \text{L}^{-1}$ and HR_{max} of $193 \pm 7 \text{ bpm}$ and $188 \pm 7 \text{ bpm}$ were reported for 13 young competition cyclists undertaking HIIT consisting of 40 s exercise/20 s rest or 30 s exercise/30 s rest at $135\% \text{ VO}_{2\text{max}}$, respectively (Nicoló et al., 2012). In another sport modality, karate, which because of its competitive characteristic is intermittent and combats last 3 min, high levels of lactate and cardiovascular stress were reported after a combat: [lactate]_{final} $11.2 \pm 2.2 \text{ mmol} \cdot \text{L}^{-1}$ and HR = $177 \pm 14 \text{ bpm}$, $91 \pm 5\% \text{ HR}_{\text{max}}$ (Chaabene et al., 2014). These results are similar to those obtained in our three CrossFit® WODs. In yet another sport, this time a team sport, rugby, Granatilli et al., (2014) obtained [lactate] of $8.7 \pm 1.7 \text{ mmol} \cdot \text{L}^{-1}$ (half time) and of $11.2 \pm 1.4 \text{ mmol} \cdot \text{L}^{-1}$ (end match) along with HR_{max} of $92.3 \pm 5.5\%$ (half time) and $92.4 \pm 4.0\%$ (end match) in two international rugby matches.

Exercise intensity in fitness modalities: We also compared our data with those reported for indoor cycling sessions conducted at high intensity (Barbado et al., 2017). In this last study, HR_{mean} and HR and RPE data were recorded across three 15 min time intervals in 300 individuals with indoor cycling experience. HR_{mean} was $145 \pm 16 \text{ bpm}$ ($86\% \text{ HR}_{\text{max}}$) for the session, and HR_{mean} and RPE were

$135 \pm 17 \text{ bpm}$ and 5.4 ± 1.7 for the first interval (0-15 min), $149 \pm 16 \text{ bpm}$ and 7.1 ± 1.3 for the second interval (15-30 min), and $154 \pm 17 \text{ bpm}$ and 7.1 ± 2.4 for the third interval (30-45 min) respectively (Barbado et al., 2017). The HR values obtained in the present study for the CrossFit® WODs were higher. Thus, the HR_{mean} recorded for the “Cindy” and skip rope double unders was 23% higher compared to indoor cycling (difference ~33 bpm) and the HR_{mean} recorded for the power cleans was ~18% higher compared to the indoor cycling (difference 26 bpm). The mean RPE calculated for the 3 intervals of the indoor cycling session was 6.6, or 66%. When expressed as percentages, our RPEs were 89% (WOD 1), 79% (WOD 2) and 78% (WOD 3) and therefore considerably higher.

However, we observed moderate correlations between HR and RPE in the CrossFit® sessions ($r = 0.314$; $p = 0.011$ for RPE-cardio in WOD 1 and $r = 0.361$, $p = 0.000$ RPE-general in WOD 2), similar to those detected in the indoor cycling session by Barbado et al. (minutes 15 ($r = 0.336$; $p < 0.01$), 30 ($r = 0.291$; $p < 0.01$), and 45 ($r = 0.459$; $p < 0.01$)) (Barbado et al., 2017) while slightly stronger correlations were reported for a cycle ergometer session conducted at the lactate threshold ($2.5 \text{ mmol} \cdot \text{L}^{-1}$) (RPE-general $r = 0.430$; RPE-muscular $r = 0.480$; RPE-cardio $r = 0.410$) (Green et al., 2005).

In another Spinning® study by Piacentini et al., (2009), HR_{mean} of $163 \pm 8 \text{ bpm}$ ($86\% \text{ HR}_{\text{max}}$) were obtained in men, and of $154 \pm 7 \text{ bpm}$ in women ($86\% \text{ HR}_{\text{max}}$), higher than the rates observed in the study by Barbado's group (2017). Notwithstanding, greater intensities were recorded in the CrossFit® WODs tested here (~90 % HR_{max}).

One study examined relationships among HR, RPE and [lactate] as variables quantifying exercise intensity in HIIT on a cycle ergometer (5 sets x 2 min rest 3 min), and found moderate association during exercise both for HR-RPE ($r = 0.63$) and for [lactate]-RPE ($r = 0.43$) (Green et al., 2006). These correlations are stronger than those recorded in the CrossFit® sessions. In contrast, correlations between [lactate] and HR were high in the WODs (WOD 1: 0.938 , $p < 0.000$; WOD 2: 0.915 , $p < 0.000$; WOD 3: 0.933 , $p < 0.000$), yet were not significant ($r = 0.13$) during a continuous cycle ergometry exercise at the intensity of the lactate threshold (Green et al., 2005).

Muscular fatigue: In the present study, we assessed muscular fatigue in response to the different WODs through a loss of capacity to generate muscular power in the CMJ test (Garnacho-Castaño et al., 2015b; Maté-Muñoz et al., 2017; Sánchez-Medina and González-Badillo, 2011). The variables jump H, V_{max}, APR and APT were recorded 3 minutes after completing each WOD as it has been proposed that CMJ test results before this time point reflect a lack of recovery of phosphocreatine reserves (Maté-Muñoz et al., 2017). In the “Cindy” and power clean WODs, significant losses were produced in the variables jump height H (7.3% , 95% CI = $1.742 - 3.452$, ES = 1.094 , $p = 0.000$, and 8.1% , 95% CI = $1.81 - 3.70$, ES = 1.050 , $p = 0.000$, respectively), take-off velocity V_{max} (13.8% 95% CI = $0.23 - 0.46$, ES = 1.089 , $p = 0.000$, and 3.3% CI 95% = $0.05 - 0.13$, ES = 0.872 , $p = 0.000$ respectively), average power relative APR (4.6% , CI 95% = $0.49 - 2.35$, ES =

0.552, $p = 0.004$ and 8.3%, CI 95% = 1.58 – 3.13, $ES = 1.091$, $p = 0.000$, respectively) and average power total APT (4.2%, 95% CI = 27.95 – 169.30, $ES = 0.502$ and 8.2%, CI 95% = 111.26 – 245.38, $ES = 0.958$, $p = 0.000$, respectively). In both these WODs, all variables showed high confidence levels and a large effect size (Cohen's $d > 0.8$) (Cohen, 1988) except for a medium effect size (Cohen's $d > 0.5$) for APR and APT in the "Cindy" WOD. In contrast, in the skip rope double unders WOD, while postexercise values were lower than preexercise ones, differences were not significant (H 4.3%, V_{max} 1%, APR 2%, APT 1.8%). These data are in line with those obtained in prior work (Maté-Muñoz et al., 2017), in which we observed that H , V_{max} , APR, APT, peak power relative and peak power total for skip rope double unders differed significantly from their preexercise values in CMJs performed between sets 2, 4, 6 and 8 without a 3 min rest period, suggesting the recovery of phosphocreatine levels. One of the possible explanations for these results could be the introduction of rest periods which despite being only 10 s following each set proved adequate for avoiding muscular fatigue thus maintaining muscle stiffness (Romero-Rodríguez and Tous, 2010). However, in the "Cindy" and power clean WODs, this loss of jump ability could have been the outcome of the fatigability of type II muscle fibers, which are those predominantly used in high intensity exercise as they are more dependent on glycolytic energy metabolism (Pérez et al., 2003), reflected by higher [lactate] levels recorded at the end of exercise ("Cindy" 12 mmol·L⁻¹, power cleans 11.5 mmol·L⁻¹). Moreover, this jump ability loss could be related to a loss of muscle-tendon stiffness as the high intensity and high exercise volume would give rise to an incapacity for adequate muscle contraction (Romero-Rodríguez and Tous, 2010). In a recent study, significant thickening of the Achilles and patellar tendons was observed just after performing a CrossFit® WOD at high intensity [5 x 5 sets of loaded squats at 50 kg (males)/ 30 kg (females); 10 box jumps (males)/50 cm (females) box], and 15 skip rope double unders (Fisker et al., 2017). This thickening of the tendons involved in the exercise could thus reduce jump ability related to diminished muscle-tendon stiffness as one of the causes of muscle fatigue. Further work is needed to explore the mechanisms leading to reduced muscular fatigue in CrossFit®.

When WODs were compared in terms of jump ability, we only observed significantly lower V_{max} for "Cindy" compared to the double under and power clean workouts ($p < 0.01$) and APR for the power clean WOD compared to the skipping double under WOD ($p = 0.49$). Possibly, the longer execution time of "Cindy" was responsible for the difference in V_{max} . In contrast, the skip rope double unders gave rise to the higher V_{max} and APR, indicating it was the WOD that generated least muscular fatigue out of the three.

The regression lines relating blood lactate levels to jump height and power losses revealed only weak relationships ($|R^2| < 0.30$) among these variables. Some authors have related jump H to [lactate], reporting moderate ($|R^2| = 0.675$) (Gorostiaga et al., 2010) or even robust ($|r| = 0.970$) correlation (Sánchez-Medina and González-Badillo, 2011). Perhaps one of the reasons for the weak correlation detected here was the time point selected for the CMJ

postexercise. Hence, in the studies by Gorostiaga et al., (2010) and Sánchez-Medina and González-Badillo (2011), CMJs were performed 1 min and immediately after exercise, respectively, while we allowed a 3 min rest period before the test, which is sufficient to replenish phosphocreatine levels. Accordingly, while in WODs 1, 2 and 3, jump height losses of 7.3% ($p < 0.05$), 4.3% ($p > 0.05$) and 8.1% ($p < 0.05$) respectively were produced, in other studies, pre-postexercise height losses were as high as 12.4% ($p < 0.05$) (Gorostiaga et al., 2010) or 11-19% ($p < 0.05$) (Sánchez-Medina and González-Badillo, 2011). However, according to data from our laboratory (Garnacho-Castaño et al., 2015a; Garnacho-Castaño et al., 2015b), lactate levels could neither be correlated with jump H ($|R^2| = 0.0278$, $|R^2| = 0.000$), and H only dropped by 4.8% and 6.4% respectively in the two studies following 21 sets x 15 repetitions of a loaded half-squat conducted at 25% 1RM. Hence, the time after exercise at which the CMJ is performed seems to be a determining factor. If the CMJ is executed immediately after exercise, jump H is significantly reduced, because, among other factors, high energy phosphate stores are depleted and H losses in the double under WOD were observed to considerably recover at 3 min postexercise (Maté-Muñoz et al., 2017). We would therefore recommend this 3 min period if the objective is to quantify muscle fatigue so that we can be sure that mechanical variables such as jump height are not exclusively dependent on phosphocreatine reserves.

Although our results provide useful information regarding the intensity of exercise and muscular fatigue induced by each of the Crossfit® WODs, a limitation of our study was that the order of the different Crossfit® sessions was not random and participants completed the same sessions each day.

Conclusion

This study examines responses to three different modality CrossFit® workouts. Our results indicate an intensity of exercise that can be classed as vigorous in all three WODs. Such high intensities of exercise have been related to cardioprotective benefits and described as a better way of improving VO_{2max} compared to more moderate work intensities. However, trainers and exercise professionals need to be cautious when prescribing such high training intensities by making sure that individuals assigned to any Crossfit® program are free of any cardiovascular or respiratory conditions or injuries that could jeopardize their health. The muscular fatigue observed here for the "Cindy" and power clean WODs, but not for the skip rope double unders, suggests that for any high intensity exercise, recovery periods are essential to avoid muscle fatigue and injury. Hence, by personalizing the intensity of exercise in subjects starting Crossfit®, these WOD modalities ("Cindy" and power clean) can be prescribed, first incorporating rest intervals or a recovery period in the middle of a session. As the subject acquires beneficial adaptations, this recovery period can be gradually shortened and the work time increased until the exact duration of each WOD.

Although our study participants lacked experience with Crossfit® and no subject participated in Crossfit®

Games, they were all well-versed in strength training. Thus, while the levels of exercise intensity and muscular fatigue reported here could be valid for persons deciding to take up Crossfit®, in high-level athletes these intensities of exercise and muscular fatigue will perhaps be lower. There is therefore a need for studies providing similar data to the present but conducted in elite athletes.

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Key points

- A vigorous intensity of exercise was noted in “Cindy”, Double Skip Rope jumps and Power Cleans WODs.
- Such high intensities of exercise have been related to cardioprotective benefits and described as a better way of improving $\text{VO}_{2\text{max}}$ compared to more moderate work intensities
- However, trainers and exercise professionals need to be cautious when prescribing such high training intensities by making sure that individuals assigned to any Crossfit® program are free of any cardiovascular or respiratory conditions or injuries that could jeopardize their health.
- The muscular fatigue observed here for the “Cindy” and Power Cleans WODs, but not for the Skip Rope Double Unders, suggests that for any high intensity exercise, recovery periods are essential to avoid muscle fatigue and injury.

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