Journal of Physical Education and Sport ® (JPES), Vol. 23 (issue 3), Art 88, pp. 714 - 721, March 2023
online ISSN: 2247 - 806X; p-ISSN: 2247 – 8051; ISSN - L = 2247 - 8051 © JPES

Original Article

Effect of lower limb fatigue and performance prediction in CrossFit®

TÚLIO BANJA[1], CLÁUDIO OLIVEIRA ASSUMPÇÃO[2], THIAGO PIRES[3],
CHRISTIAN EMMANUEL TORRES CABIDO[4], ROGÉRIO CÉSAR FERMINO[5], ROSANE ANDRADE[6],
TATIANA ACIOLI[7], MARIA DO SOCORRO CIRILO-SOUSA[8], FELIPE JOSÉ AIDAR MARTINS[9],
SAULO FERNANDES MELO OLIVEIRA[10], THIAGO MATTOS FROTA DE SOUZA[11]

[1]Institute of Physical Education and Sports, Post-graduation Program in Physiotherapy and Functioning, Federal University of Ceará, Fortaleza, CE, BRAZIL;
[2]Department of Sports Sciences, Institute of Health Sciences, Federal University of Triângulo Mineiro, Uberaba, BRAZIL;
[3]Institute of Physical Education and Sports, Federal University of Ceará, Fortaleza, CE, BRAZIL;
[4]Department of Physical Education, Post-graduation program in Physical Education/ Federal University of Maranhão (UFMA), São Luís, MA, BRAZIL;
[5]Postgraduate Program in Physical Education. Research Group in Environment, Physical Activity, and Health. Federal Technological University of Paraná, Curitiba, and Physical Education Graduate Program, Federal University of Paraná, Curitiba, PR, BRAZIL;
[6]Unigrande – University Center Fortaleza, Fortaleza, Ceará, BRAZIL;
[7]UNIFBV – University Center, Recife, Pernambuco, BRAZIL;
[8]Graduate Program Association of Physical Education, Federal University of Paraíba (UFPB), João Pessoa, Brazil, and Department of Physical Education, Regional of University (URCA), Crato, BRAZIL;
[9]Department of Physical Education, Federal University of Sergipe (UFS), São Cristóvão, SE, BRAZIL;
[10] Physical Education Graduate Program, Federal University of Pernambuco, Recife, Pernambuco, BRAZIL;
[11] Applied Kinesiology Laboratory–LCA, School of Physical Education, University of Campinas. Campinas, SP, BRAZIL.

Published online: March 31, 2023
(Accepted for publication March 15, 2023)
DOI:10.7752/jpes.2023.03088

Abstract:
Background: The CrossFit® training program, aimed at improving fitness levels, is gaining a significant number of followers worldwide as there is a growing demand for physical exercise and sports to promote good health and avoid a sedentary lifestyle. **Aim:** The present study aimed to verify the effect of a single CrossFit® training session on the lower-limb relative power and to correlate physical components of body composition, lower-limb relative power, and practice time with physical performance in the Fran benchmark. **Material and methods:** 21 volunteers (10 males and 11 females), aged 35.7 ± 6.2 years, with a body mass index (BMI) of 26.7 ± 3.1 kg/m² and practice time of 40.8 ± 33.1 months, participated in the study. Before and after training, the following variables were evaluated: jump height, lower-limb relative power, and Rating of Perceived Exertion (RPE), as well as training duration. **Results:** Lower-limb relative power showed significant differences between the pre- and post-training instants for men and women (♂ = 27.1 ± 2.1 W/kg, ♀ = 22.8 ± 2.6 W/kg; $p < 0.001$) and (♂ = 26.4 ± 1.6 W/kg, ♀ = 22.3 ± 2.4 W/kg; $p < 0.001$), respectively, with a significant reduction in power for men ($p < 0.001$) ($d = 0.42$; 95% CI: -0.35 to 1.19) and women ($p < 0.005$) ($d = 0.17$; 95% CI: -0.83 to 1.18). Only practice time correlated with Fran's training duration time ($r = -0.676$; $p < 0.01$). **Conclusion:** The results suggest that a single CrossFit® training session can lead to reduced lower limb strength and power and that the practice time is related to the performance of practitioners.
Key Words*:* Vertical Jump, Conditioning, Muscle fatigue, Biomechanics

Introduction

Physical training encompasses a range of variables unique to each modality. CrossFit® is a training program designed to improve fitness levels (strength, muscle power, cardiorespiratory capacity, and body composition) through high-intensity, short-duration exercises (Carreker & Grosicki, 2020). These exercises include weightlifting, gymnastics, and calisthenics using body weight (Feito et al., 2018). Workouts are managed daily and called the workout of the day (WOD) (Maté-Muñoz et al., 2017). Participants receive a score to track their progress.

CrossFit® utilizes benchmark workouts named after heroes or women, such as the Fran workout. This workout is a fast, predominantly anaerobic WOD. Its results are commonly used as a dependent variable for performance analysis (Leitão et al., 2021; Cavedon et al., 2020). Fran's performance is determined by the

Corresponding Author: CLÁUDIO OLIVEIRA ASSUMPÇÃO, E-mail: claudio.assumpcao@uftm.edu.br

shortest time to completion, leading to high-speed movement execution, which characterizes high-intensity WODs and results in fatigue and decreased muscle strength.

Competitions occur at regional, national, and international levels. Competitors' performance has been explained by physiological variables (Barbieri et al., 2017; Martínez-Gómez et al., 2020), such as maximal oxygen consumption, maximal anaerobic power output, upper and lower limb strength/power (Meier et al., 2021; Tibana et al., 2018), and body composition variables like fat percentage (Carreker & Grosicki, 2020; Dexheimer et al., 2019). These variables possess varying predictive capabilities for explaining competitors' performance (Dexheimer et al., 2019), as each competition features different exercises, repetitions, and strategies, such as completing a specific number of repetitions in the least amount of time (as in Fran training) or performing as many repetitions as possible (AMRAP) (Schlegel, 2020).

Some authors have suggested that body composition is a more reliable performance predictor than maximal oxygen uptake and anaerobic power output (Carreker & Grosicki, 2020; Mangine et al., 2020). However, most tests have been conducted in laboratory settings (Zeitz et al., 2020), which could differ from tasks required during competitions, contradicting the principle of specificity. For instance, assessing lower limb power output on a cycle ergometer (Carreker & Grosicki, 2020; Mangine et al., 2020; Martínez-Gómez et al., 2019) instead of estimating it through jumping protocols. The countermovement jump (CMJ) is commonly used to assess lower limb power (Maté-Muñoz et al., 2018; Maia et al., 2019) and is a predictor of neuromuscular and metabolic fatigue (Maté-Muñoz et al., 2017; Maté-Muñoz et al., 2018; Wu et al., 2019). However, few studies have employed CMJ in Fran assessments (Peña et al., 2021; Larsen et al., 2020).

Evaluating CrossFit® using specific exercises not only offers ecological validity but could also provide consistent information about the WOD and performance-explaining variables. In Fran training, for example, using movements present in the WOD for evaluation (thrusters and pull-ups) shows correlations of r=-0.82 and r=-0.59, respectively, with performance (Leitão et al., 2021). However, this approach generates a methodological limitation in standardizing tests because each WOD has specific characteristics, and some variables could influence comparisons with different benchmarks (Mangine et al., 2020; Butcher et al., 2015). Testing should have broader applicability rather than merely correlating the maximum number of repetitions of benchmark exercises or maximum repetition to performance (Leitão et al., 2021).

Although it is well-documented in the literature that physiological variables can explain the performance of CrossFit® practitioners, there is a lack of evidence regarding tests that use specific actions related to this modality. As a result, some gaps need to be addressed, particularly concerning monitoring neuromuscular and morphological aspects. It is possible that some of the characteristics of CrossFit® training can be evaluated using simple methods, mainly if they do not rely solely on these movements.

More research is needed better to understand the physiological and biomechanical aspects of CrossFit® training. Future studies should focus on developing tests that use specific actions related to this modality while considering simple methods for evaluating neuromuscular and morphological characteristics. By doing so, we can gain a more comprehensive understanding of the demands of CrossFit® training and ultimately develop more effective training strategies for practitioners.

Thus, certain gaps must be addressed, particularly regarding the monitoring of neuromuscular and morphological aspects. It is possible that some characteristics of CrossFit® training can be evaluated using simple methods, not solely relying on modality-specific movements. Our hypothesis focused on the reductions in lower limb power output during jumping and the associations between practice time, as high-intensity training can cause acute changes in participants' physical performance. In this context, the study's primary aim was to analyze the effect of a training session on lower limb muscle power in CrossFit® practitioners. The secondary objective was to understand the relationship between components of body composition, lower limb power output, and practice time with the physical performance of this session.

Material & methods

An Experimental Approach to the Problem

The present study investigated whether a training session in CrossFit® could generate fatigue in a group of recreational practitioners and identified variables that could explain performance in this session. A group of 21 practitioners volunteered to train in the Fran benchmark, a standardized workout that consists of three rounds of a 21-15-9 descending repetition scheme of Thrusters and pull-ups. All tests were performed on a single day in the morning, and the order of evaluations was body mass, height, Body Mass Index (BMI), dominant thigh circumference, time practicing in CrossFit®, jump height, and lower limb power (before and after the training session).

Subjects

A total of 21 participants (10 men and 11 women) were recruited from a CrossFit® gym. All participants were in good physical condition and had the opportunity to participate in the study. The Institutional Ethics and Human Research Committee approved the study under protocol number 3,290,772, and written consent was obtained from each participant before any testing was performed.

Procedures

Anthropometric data:

Body mass was measured using an electronic scale (Tanita BWB-800, MA, USA) accurate to 0.1 kg, and height using a stadiometer (CESCORF, São Paulo, BR) accurate to 0.01 m. We calculated BMI by dividing the weight (kg) by the squared height (m^2). To measure the circumference of the dominant thigh, we used an anthropometric tape measure (SANNY, São Paulo, BR) accurate to 0.01 m, taken at the midpoint between the inguinal point and the upper border of the patella. To do so, subjects were seated upright, with arms along the body and knees flexed at 90°, while the evaluator stood at the lateral aspect of the thigh to take the measurement.

Rating perception of exertion.

Rating of Perceived Exertion (RPE) was recorded using a scale developed by Nakamura et al. (2010). It includes 0 = "Rest", 1 = "Very, very easy", 2 = "Easy", 3 = "Moderate", 4 = "Somewhat difficult", 5 = "Difficult", 7 = "Very difficult", 10 = "Maximum Effort". Before the workout of the day (WOD), subjects were instructed to choose a descriptor that best described their level of exertion and then select a number between 0 and 10, corresponding with the level of effort they felt. The minimum value of "0" indicated absolute rest, while the maximum value of "10" represented the greatest physical effort made by the person. We recorded the RPE at the end of the WOD. To help the participants differentiate between the different levels of RPE, we provided instructions to consider a feeling of exertion involving the heart and lungs (cardiopulmonary RPE), the muscles used in the exercise (muscular RPE), or a feeling of general exertion affecting the heart, lungs, and muscles (general RPE), based on previous research by Maté-Muñoz et al. (2018).

Jump height and lower limb power output.

To calculate relative lower limb power output and jump height, we used the Countermovement Jump (CMJ). Participants performed 6 to 10 submaximal jumps to familiarize themselves with the technique until the jump movement stabilized. After a five-minute break, participants jumped six times, ten seconds between each attempt, attempting to reach the highest possible height. During the jump, participants were instructed to keep their hands fixed on their hips and their knees extended during the flight phase. A contact mat (CEFISE, São Paulo, Brazil) was used to measure the flight time, and the highest jump was used for analysis. We calculated jump height using the equation ($1/8 \times g \times t^2$), takeoff speed estimated from the time of flight by the equation ($g \times t / 2$), and lower limb power (absolute) using the takeoff speed multiplied by the body mass of each participant. To calculate relative power, we divided power (absolute) by each participant's body mass.

The Fran workout.

The Fran workout is a time-scored CrossFit® WOD consisting of three rounds of a 21-15-9 descending repetition scheme of Thrusters and pull-ups. Thrusters are performed as a squat with the bar in front of the head and resting on the shoulders, lifting the bar above the head at the end of the triple extension movement. Pull-ups use the strength of the arms to lift the body above a bar, with each valid repetition requiring lifting the chin above the bar. Participants completed a warm-up under the trainer's supervision before performing the WOD, which included running around the gym, multiple joint movements, push-ups, knee push-ups, and arm balances. The WOD was completed with a prescribed weight of 40 kg for men and 22 kg for women for the Thrusters, and pull-up variations, including butterfly and kipping, were encouraged. The time to complete all repetitions was recorded in seconds, and a coach supervised and scored the training to ensure proper movement patterns.

Statistical Analyses

To ensure the normality assumption and homogeneity of variance, we used the Shapiro-Wilk and Levene tests, respectively, and checked for outliers through a graphical examination. For statistical differences between groups (Men and Women), we performed a student t-test for unpaired data if the normality assumptions were met, or the Mann-Whitney test if not, on dependent variables including Age, Weight, BMI, Thigh circumference, practice time, Training session time, and RPE. To determine the effect of the Fran training session, we conducted a two-way ANOVA with repeated measures using a mixed model with a group (Men and Women) and time (Pre and Post) as fixed factors and subjects as random factors. Bonferroni's post hoc test was used to identify specific differences among dependent variables (jump height and relative power output) when F values were significant. We considered three types of covariance matrices and chose the model with the best fit based on the lowest BIC value.

To analyze jump height, power, and practice time x session time, we used the confidence interval and d effect size, considering trivial, small, moderate, and large effects where $d < 0.35$, 0.35-0.80, 0.80-1.50, or > 1.50, respectively (Rhea, 2004). We used Pearson's correlation test to identify possible correlations between dependent variables, interpreting coefficients as "Weak" for $0.10 \le r \le 0.30$, "Moderate" for $0.40 \le r \le 0.6$, and "Strong" for $r \ge 0.70$. To calculate intra-session reliability, we used the intraclass correlation coefficient (ICC1,1) according to Weir (2005) and Claudino et al. (2013). All six jump trials were paired, and CCI classification was interpreted as "very low" (0.00 – 0.25), "low" (0.26 – 0.49), "moderate" (0.50 – 0.50 – 0.69), "high" (0.70 – 0.89), and "very high" (0.90 – 1.0).

To understand possible intervening variables in performance, we applied the k-means cluster technique to the variable session duration (WOD) and divided volunteers into two groups (longer and shorter duration). Then, a student t-test with Welch correction was performed to compare dependent variables (age, weight, BMI, thigh circumference, practice time, jump countermovement, and relative power) between groups (longer and shorter duration time). All analyses were performed using the Statistical Package for Social Sciences™ (SPSS Inc., Chicago, IL, USA) software, version 25.0, with a 5% significance level. Descriptive results were presented as mean and standard deviation.

Results

Table 1 shows the results and variables studied, as well as the characteristics of participants.

Table 1. Characteristics of the participants and results (n=21)

	Man (n = 10) **Mean ± SD**	**Woman (n = 11)** **Mean ± SD**	**Group** **Mean ± SD**
Age (years)	34.1 ± 3.0	37.2 ± 8.1	35.7 ± 6.2
Body mass (kg)	83.3 ± 10.2	66.5 ± 7.4**	74.5 ± 12.2
Height (cm)	170.3 ± 0.05	163.1 ± 0.05**	166.5 ± 0.06
BMI (kg/m2)	28.7 ± 2.6	25.0 ± 2.3**	26.7 ± 3.1
Thigh circumference (cm)	59.6 ± 4.1	57.6 ± 4.8	58.6 ± 4.5
Time of practice (months)	41.8 ± 30.8	39.8 ± 36.6	40.8 ± 33.1
Session time (sec)	407.3 ± 147.6	472.4 ± 121.5	441.4 ± 135.3
RPE post-training	8.4 ± 0.8	8.4 ± 1.4	8.4 ± 1.0

Legend: RPE = Rating Perception of Effort. **Statistical difference between women and men ($p < 0.01$).

Figure 1 displays the countermovement jump (CMJ) results before and after the training session (WOD), with group ($p<0.01$) and time ($p<0.01$) effects being verified.

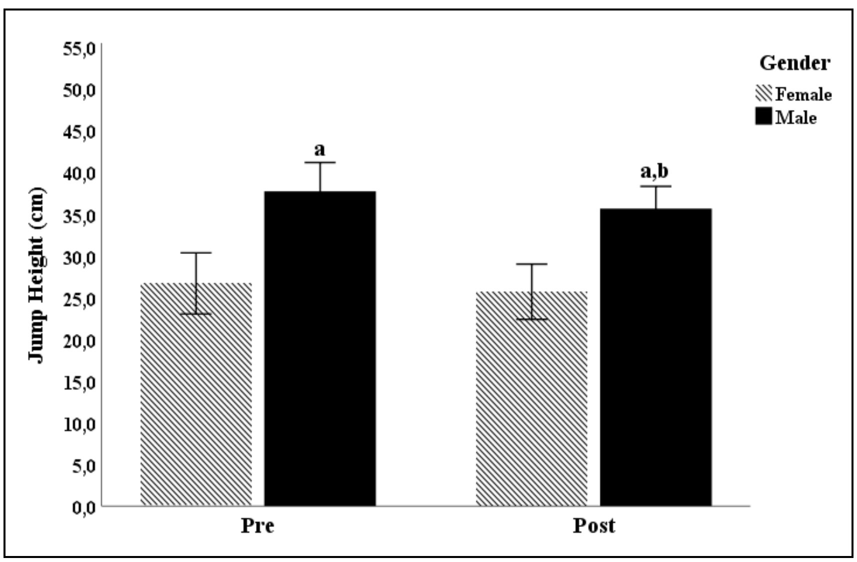

Figure 1: Comparison of jump height before and after WOD between male and female participants. **A:** Statistical difference between males and females ($p < 0.01$); **B:** Statistical difference between pre-and post-training ($p < 0.01$).

Figure 2 demonstrates the results of relative power before and after the training session (WOD), with group ($p<0.01$) and time ($p<0.01$) effects being verified.

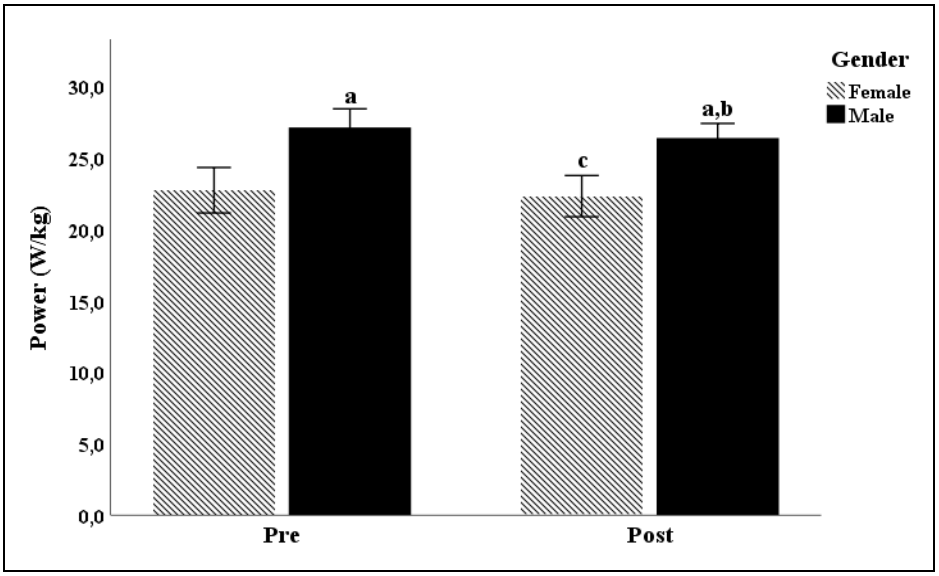

Figure 2: Comparison of relative power before and after WOD between male and female participants. **A:** Statistical difference between males and females ($p<0.01$); **B:** Statistical difference between pre-and post-training ($p<0.01$); **C:** Statistical difference between pre-and post-training times ($p<0.05$).

The reliability results for jump height were classified as very high for men ($r=0.910$; $p=0.01$), women ($r=0.948$; $p=0.01$), and overall ($r=0.987$; $p<0.01$).

The only dependent variable that correlated with Fran's training duration was the participants' practice time. In all cases, including men ($r=-0.680$; $p=0.03$), women ($r=-0.720$; $p=0.01$), and overall ($r=-0.676$; $p<0.01$), a longer practice time resulted in a shorter WOD duration. No other significant correlations were found to explain performance. To better understand the intervening factors of performance, a cluster analysis was conducted based on the duration of the WOD, and Figure 3 compares practice time between the group with longer and shorter WOD duration.

Figure 3 depicts that the group with the shortest WOD duration had the longest practice time, with a statistically significant difference between the groups ($p<0.01$). Moreover, no other significant differences were found for the other dependent variables.

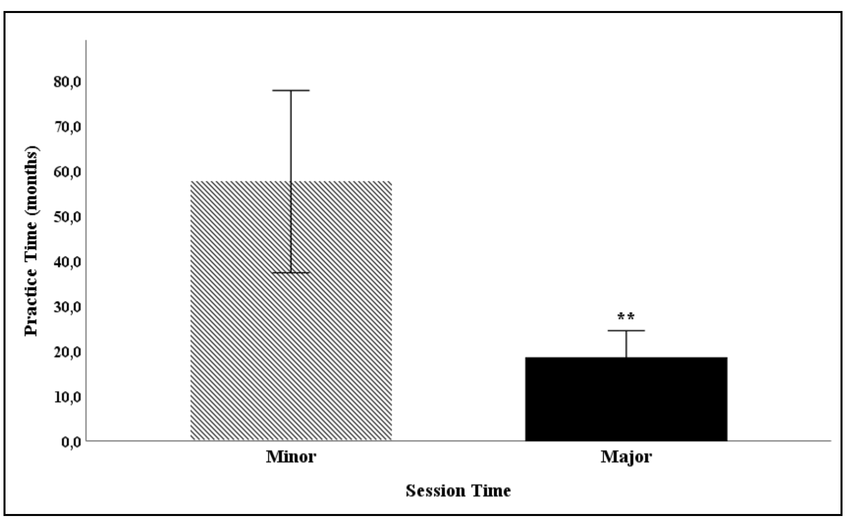

Figure 3: Comparison of practice time between participants with less and more WOD duration. **Statistical difference between Lowest and Highest groups ($p<0.01$).

Discussion

This study aimed to investigate the effect of a training session on lower limb muscular power in CrossFit™ practitioners and to evaluate the relationship between body composition, lower limb power, and practice time with physical performance during this session. The study found that Fran training leads to fatigue that negatively impacts the ability to generate lower limb power and that practice time is a factor that influences the achievement of the lowest execution time of this benchmark.

Regarding variables that could explain performance in Fran, we found no significant correlations between anthropometric variables and session time. BMI and thigh circumference were unable to explain performance due to the limitations of BMI in differentiating between fat mass and fat-free mass, hindering the identification of the real effect on performance (Gómez-Landero & Frías-Menacho, 2020). Conversely, some studies have highlighted a relationship between body composition variables and performance in WODs (Carreker & Grosicki, 2020; Mangine et al., 2020; Dexheimer et al., 2019). However, fat, and non-fat percentages were found to be more reliable concerning performance in extreme training programs, as they allow for a better understanding of the relationship between body composition and performance in CrossFit® practitioners. A larger muscle mass and an increased ratio between fat-free mass and fat percentage allow us to generate more strength and power. However, using only BMI and perimetry may difficult the interpretation of the phenomena necessary to establish a more consistent relationship between body composition and performance in CrossFit® practitioners.

Wu et al. (2019) found that the countermovement jump (CMJ) is an efficient test to quantify neuromuscular fatigue and estimate the loss of muscle capacity to produce force after strenuous exercise. Tests to assess lower limb power, in conjunction with other physiological variables, have "very high" determinants of performance in CrossFit® competitors (Martínez-Gómez et al., 2020). In this study, jump height and relative power output were higher in men than women, which was expected due to differences in strength between genders. As for relative lower limb power, there was a decrease in the ability to generate lower limb power after performing the WOD. These results corroborate Maté-Muñoz et al. (2017), who evaluated three benchmarks, each with a predominance of gymnastics, calisthenics, and weightlifting. Furthermore, fatigue directly affects the ability to generate strength and muscle power by degrading the stretching and shortening cycle, which leads to a significant reduction in force and power output production (Nicol et al., 2006).

The impairment of neuromuscular function in intense activities, such as CrossFit® , can be explained by central and peripheral mechanisms, such as decreased neural unity, impaired excitability of the motor neuron, and failure in excitation-contraction coupling, among others (Assumpção et al., 2020). Such specific changes within the central nervous system resulting in strength loss related to high-intensity exercise are not yet fully understood. However, a greater reduction in activation has been observed at higher intensities as compared to activities where the overload is gradually increased. This reduces the ability to generate force after high-intensity workouts, such as Fran. The 45 thruster squats during the WOD can cause muscle fatigue in the main muscles that move the knee and hip joints. Since the goal of the training is to complete the repetitions in the shortest possible time, the speed of the movements is fast, which is consistent with an activity that demands high intensity.

When using RPE to measure exercise intensity perception, responses such as "difficult" and "very difficult" were observed, just as those reported by Maté-Muñoz et al. (2017) and Drum et al. (2017). For these authors, such responses denote that participants thought the exercises were highly intense and might be above the ventilatory threshold. Other studies have pointed to RPE as one of the most consistent ways to determine exercise intensity (Nakamura et al., 2010; Rascon et al., 2019); therefore, it can also be used along with other measures to estimate the level of fatigue experienced during exercise. This rating is a low-cost, highly practical, and easy-to-use tool for professionals and exercisers who aim to evaluate the internal load of their training. Its use can thus improve the planning of training load at different times (micro, meso, and macrocycles), as well as reviewing and resuming planning that may have failed (Maia et al., 2019).

As for overall performance, the time required to complete a training session in our study was longer than in other studies. For instance, Dexheimer et al. (2019) reported values of 237.9 ± 83.9 seconds for men and 295.4 ± 42.8 seconds for women, while Butcher et al. (2015) reported an average of 203±48 seconds for both genders. These findings suggest that the conditioning level of our participants was lower than that of the authors of these studies. This can be explained by the fact that our sample consisted of recreational CrossFit® practitioners. However, the duration of the experience was like other studies, with 43.2 ± 29.4 months, 46.3 ± 24.2 months (Dexheimer et al., 2019), 46.3±24.2 months (Butcher et al., 2015), 42.5 ± 1.7 months (Barbieri et al., 2017), and 46.8 ± 30.7 months (Carreker & Grosicki, 2020).

Practice time was found to have a strong inverse association with the Fran training time for both men and women. Previous studies have reported that weekly training strongly correlates with performance on benchmarks, including Fran (Peña et al., 2021). Several authors have also shown inverse associations, especially when the benchmark evaluated aims to achieve the maximum number of repetitions in the shortest possible time (Barbieri et al., 2017; Dexheimer et al., 2019; Butcher et al., 2015). Bellar et al. (2015) were the only ones to investigate the possible influence of time of experience on performance. They compared experienced and inexperienced CrossFit® athletes in terms of aerobic capacity and anaerobic power and suggested that a history of participation in CrossFit® competitions is a key component of WOD performance. This information is relevant and could be a variable to explain performance since individuals with more practice time possess more muscular strength and experience with standardized training, leading to a greater capacity to manage the effort during the session. This would minimize the effects of fatigue and maintain optimal performance throughout the workout. Our findings support this notion, as shown in Figure 3, where exercisers with longer practice time achieved significantly shorter session duration than those with less practice time.

Limitations

We acknowledge several limitations of our study. Firstly, most of the analyzed CrossFit® practitioners were considered recreational, which may have influenced the predicting performance variables due to their experience level or familiarity (Zeitz et al., 2020). As such, it remains unclear whether these variables would be associated with the performance of more experienced practitioners. Additionally, our results reflect only a cross-sectional evaluation of the group, and their conditioning may change over time. Moreover, it is possible that using a different WOD for the tests could result in different predictive abilities. Therefore, further research must identify the most appropriate match between tests, variables, and selected benchmarks.

Conclusions

Our research shows that training with the CrossFit® Fran program can lead to a decrease in jump height, which is similar to the results observed in fatigue determination protocols. Specifically, Fran's training appears to acutely impair the lower limb's ability to produce strength and power. Therefore, using this benchmark to induce or evaluate fatigue to monitor training progress may be possible. Evaluating and adjusting the training loads according to the practitioner's reality is essential.

We found that the amount of time spent practicing CrossFit® was a better predictor of Fran's total training time compared to anthropometric variables and should be considered as a variable that can help explain the performance of recreational practitioners. However, further research is still needed to understand better how to control the load using field tests or specific tests in CrossFit®. This will allow for a better association between these variables and performance criteria, ultimately leading to more effective training strategies for practitioners.

Conflicts of interest - The authors declare no conflict of interest.

References:

Assumpção, C., Barreto, R. V., de Lima, L. C. R., Cardozo, A. C., de Lima Montebelo, M. I., Catarino, H. R. C., Greco, C. C., & Denadai, B. S. (2020). A single bout of downhill running attenuates subsequent level running-induced fatigue. *Scientific Reports*, *10*(1), 18809. https://doi.org/10.1038/s41598-020-76008-2

Barbieri, J. F., Correia, R. F., Castaño, L. A. A., Brasil, D. V. C., & Ribeiro, A. N. (2017). Comparative and correlational analysis of the performance from 2016 crossfit games high-level athletes. *Manual Therapy, Posturology & Rehabilitation Journal*, *15*(January), 1–4. https://doi.org/10.17784/mtprehabjournal.2017.15.521

Bellar, D., Hatchett, A., Judge, L., Breaux, M., & Marcus, L. (2015). The relationship of aerobic capacity, anaerobic peak power and experience to performance in HIT exercise. *Biology of Sport*, *32*(4), 315–320. https://doi.org/10.5604/20831862.1174771

Butcher, S., Neyedly, T., Horvey, K., & Benko, C. (2015). Do physiological measures predict selected CrossFit® benchmark performance? *Open Access Journal of Sports Medicine*. https://doi.org/10.2147/oajsm.s88265

Carreker, J. D., & Grosicki, G. J. (2020). Physiological Predictors of Performance on the CrossFit "Murph" Challenge. *Sports*, *8*(7), 92. https://doi.org/10.3390/sports8070092

Cavedon, V., Milanese, C., Marchi, A., & Zancanaro, C. (2020). Different amount of training affects body composition and performance in High-Intensity Functional Training participants. *PLOS ONE*, *15*(8), e0237887. https://doi.org/10.1371/journal.pone.0237887

Claudino, J. G., Mezêncio, B., Soncin, R., Ferreira, J. C., Valadão, P. F., Takao, P. P., Bianco, R., Roschel, H., Amadio, A. C., & Serrão, J. C. (2013). Development of an individualized familiarization method for vertical jumps. *Brazilian Journal of Sports Medicine*, *19*(5), 359–362. https://doi.org/10.1590/S1517-86922013000500012

Dexheimer, J. D., Schroeder, E. T., Sawyer, B. J., Pettitt, R. W., Aguinaldo, A. L., & Torrence, W. A. (2019). Physiological Performance Measures as Indicators of CrossFit® Performance. *Sports*, *7*(4), 93. https://doi.org/10.3390/sports7040093

Drum, S. N., Bellovary, B. N., Jensen, R. L., Moore, M. T., & Donath, L. (2017). Perceived demands and postexercise physical dysfunction in CrossFit® compared to an ACSM based training session. *The Journal of Sports Medicine and Physical Fitness*, *57*(5), 604–609. https://doi.org/10.23736/S0022-4707.16.06243-5

Feito, Y., Heinrich, K., Butcher, S., & Poston, W. (2018). High-Intensity Functional Training (HIFT): Definition and Research Implications for Improved Fitness. *Sports*, *6*(3), 76. https://doi.org/10.3390/sports6030076

Gómez-Landero, L. A., & Frías-Menacho, J. M. (2020). Analysis of Morphofunctional Variables Associated with Performance in Crossfit® Competitors. *Journal of Human Kinetics*, *73*(1), 83–91. https://doi.org/10.2478/hukin-2019-0134

Larsen, R. T., Hessner, A. L., Ishøi, L., Langberg, H., & Christensen, J. (2020). Injuries in Novice Participants during an Eight-Week Start up CrossFit Program—A Prospective Cohort Study. *Sports*, *8*(2), 21. https://doi.org/10.3390/sports8020021

Leitão, L., Dias, M., Campos, Y., Vieira, J. G., Sant'Ana, L., Telles, L. G., Tavares, C., Mazini, M., Novaes, J., & Vianna, J. (2021). Physical and Physiological Predictors of FRAN CrossFit® WOD Athlete's Performance. *International Journal of Environmental Research and Public Health*, *18*(8), 4070. https://doi.org/10.3390/ijerph18084070

Maia, N. M., Kassiano, W., Assumpção, C. O., Andrade, A. D., Fernandes, R. J., de Jesus, K., Simim, M. A. M., & Medeiros, A. I. A. (2019). Neuromuscular and autonomic responses during a crossfit® competition: A case study. *Trends in Sport Sciences*, *26*(4), 165–170. https://doi.org/10.23829/TSS.2019.26.4-4

Mangine, G. T., Tankersley, J. E., McDougle, J. M., Velazquez, N., Roberts, M. D., Esmat, T. A., VanDusseldorp, T. A., & Feito, Y. (2020). Predictors of CrossFit Open Performance. *Sports*, *8*(7), 102. https://doi.org/10.3390/sports8070102

Martínez-Gómez, R., Valenzuela, P. L., Alejo, L. B., Gil-Cabrera, J., Montalvo-Pérez, A., Talavera, E., Lucia, A., Moral-González, S., & Barranco-Gil, D. (2020). Physiological Predictors of Competition Performance in CrossFit Athletes. *International Journal of Environmental Research and Public Health*, *17*(10), 3699. https://doi.org/10.3390/ijerph17103699

Martínez-Gómez, R., Valenzuela, P. L., Barranco-Gil, D., Moral-González, S., García-González, A., & Lucia, A. (2019). Full-Squat as a Determinant of Performance in CrossFit. *International Journal of Sports Medicine*, *40*(09), 592–596. https://doi.org/10.1055/a-0960-9717

Maté-Muñoz, J. L., Lougedo, J. H., Barba, M., Cañuelo-Márquez, A. M., Guodemar-Pérez, J., García-Fernández, P., Lozano-Estevan, M. del C., Alonso-Melero, R., Sánchez-Calabuig, M. A., Ruíz-López, M., de Jesús, F., & Garnacho-Castaño, M. V. (2018). Cardiometabolic and muscular fatigue responses to different crossfit® workouts. *Journal of Sports Science and Medicine*, *17*(4), 668–679.

Maté-Muñoz, J. L., Lougedo, J. H., Barba, M., García-Fernández, P., Garnacho-Castaño, M. V., & Domínguez, R. (2017). Muscular fatigue in response to different modalities of CrossFit sessions. *PLoS ONE*, *12*(7), 1–17. https://doi.org/10.1371/journal.pone.0181855

Meier, N., Rabel, S., & Schmidt, A. (2021). Determination of a CrossFit® Benchmark Performance Profile. *Sports*, *9*(6), 80. https://doi.org/10.3390/sports9060080

Nakamura, F. Y., Moreira, A., & Aoki, M. S. (2010). Training load monitoring: is the session rating of perceived exertion a reliable method? *Journal of Physical Education/UEM*, *21*(1). https://doi.org/10.4025/reveducfis.v21i1.6713

Nicol, C., Avela, J., & Komi, P. V. (2006). The Stretch-Shortening Cycle. *Sports Medicine*, *36*(11), 977–999. https://doi.org/10.2165/00007256-200636110-00004

Peña, J., Moreno-Doutres, D., Peña, I., Chulvi-Medrano, I., Ortegón, A., Aguilera-Castells, J., & Buscà, B. (2021). Predicting the Unknown and the Unknowable. Are Anthropometric Measures and Fitness Profile Associated with the Outcome of a Simulated CrossFit® Competition? *International Journal of Environmental Research and Public Health*, *18*(7), 3692. https://doi.org/10.3390/ijerph18073692

Rascon, J., Trujillo, E., Acuna, F. J. M., & Gurovich, A. N. (2019). Differences in Determining Exercise Intensity in Males and Females. *Medicine & Science in Sports & Exercise*, *51*(Supplement), 765–766. https://doi.org/10.1249/01.mss.0000562781.85673.6c

Rhea, M. R. (2004). Determining the Magnitude of Treatment Effects in Strength Training Research Through the Use of the Effect Size. *The Journal of Strength and Conditioning Research*, *18*(4), 918. https://doi.org/10.1519/14403.1

Schlegel, P. (2020). CrossFit® Training Strategies from the Perspective of Concurrent Training: A Systematic Review. *Journal of Sports Science & Medicine*, *19*(4), 670–680. http://www.ncbi.nlm.nih.gov/pubmed/33239940

Tibana, R. A., de Farias, D. L., Nascimento, D. C., Da Silva-Grigoletto, M. E., & Prestes, J. (2018). Correlation of muscle strength with weightlifting performance in CrossFit® practitioners. *Andalusian Journal of Sports Medicine*, *11*(2), 84–88. https://doi.org/10.1016/j.ramd.2015.11.005

Weir, J. P. (2005). Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. *Journal of Strength and Conditioning Research*, *19*(1), 231–240. https://doi.org/10.1519/15184.1

Wu, P. P.-Y., Sterkenburg, N., Everett, K., Chapman, D. W., White, N., & Mengersen, K. (2019). Predicting fatigue using countermovement jump force-time signatures: PCA can distinguish neuromuscular versus metabolic fatigue. *PLOS ONE*, *14*(7), e0219295. https://doi.org/10.1371/journal.pone.0219295

Zeitz, E. K., Cook, L. F., Dexheimer, J. D., Lemez, S., Leyva, W. D., Terbio, I. Y., Tran, J. R., & Jo, E. (2020). The Relationship between CrossFit® Performance and Laboratory-Based Measurements of Fitness. *Sports*, *8*(8), 112. https://doi.org/10.3390/sports8080112