



Assessment and characterization of physiological and biomechanical responses to CrossFit® benchmark workouts in experienced crossfitters

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Supervisor

Ricardo J. Fernandes, Ph.D

Co-supervisor

Daniel Moreira-Gonçalves, Ph.D

Manoel Juarez Marinho Rios

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Dedication

To my mother, Olga Marinho Rios

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Abstract

Understanding crossfitters responses to daily loads is a challenge in prescribing various CrossFit® workouts. We aimed to evaluate and characterize the physiological and biomechanical aspects of the Fran and Isabel CrossFit®. Experiments comprises: (i) the Fran CrossFit® workout (three rounds of 21, 15 and 9 front squats to overhead press plus pull-up repetitions), performed intermittently and unbroken to evaluate physiological responses and post-workout recovery; and (ii) the Isabel workout (30 snatch repetitions with 61 kg), performed at extreme intensity to characterize oxygen uptake ($\dot{V}O_2$) kinetics, energy systems contributions, total energy expenditure and biomechanical changes, particularly in relation to relevant angles. Cardiorespiratory and metabolic variables were evaluated at baseline, during and post-workouts, while muscular functions were assessed at baseline and during the recovery period. The bioenergetic profile was evaluated by considering the sum of aerobic, anaerobic lactic and anaerobic alactic contributions. 3D markerless motion capture was used to collect data along the Isabel workout. The amplitude of the fast component $\dot{V}O_2$ was higher in the Isabel workout compared with unbroken Fran workout (42.0 vs 35.8 mL·kg⁻¹·min⁻¹), contrary to the time constant (14.2 vs 23.7 s) whose mean values were higher in the unbroken Fran workout, with no differences in the time delay (4.3 vs 4.7 s, respectively) between the two workouts. The unbroken Fran workout elicited a higher peak $\dot{V}O_2$, heart rate, and aerobic contribution (62 vs 40 vs 41%) compared to Isabel and intermittent Fran workouts, which exhibited a higher anaerobic contribution (38 vs 60 vs 59%, respectively). Reduction in muscle function in jumping ability and plank prone test was observed in the recovery period from Fran workouts (intermittent and unbroken). At extreme Isabel workout intensity, maximal lift velocity and maximal lift power decreased from the initial to final phases, while the time from lift until the bar crossed the hip and shoulder decreased progressively along the workout. It is apparent that mechanical, intensity and volume differences between workout modes performed at maximal effort influence cardiorespiratory and bioenergetic profiles. This analysis provided new insights into selecting the prescription of intensity and recovery for CrossFit® workouts (and strength training) performed at maximal effort.

Resumo

Compreender as respostas dos crossfitters às cargas diárias é um desafio na prescrição de treinos de CrossFit®. O nosso objetivo foi avaliar os aspectos fisiológicos e biomecânicos dos treinos Fran e Isabel de CrossFit®. Os experimentos compreendem: (i) o treino Fran (três séries de 21, 15 e 9 repetições de agachamentos frontais para desenvolvimento acima da cabeça mais elevações), realizado de forma intermitente e contínua para avaliar as respostas fisiológicas e a recuperação pós-treino; e (ii) o treino Isabel (30 repetições de arranco com 61 kg), realizado a intensidade extrema para caracterizar a cinética do consumo de oxigénio ($\dot{V}O_2$), as contribuições dos sistemas energéticos, o gasto energético total e as alterações biomecânicas, particularmente em relação aos ângulos relevantes. As variáveis cardiorrespiratórias e metabólicas foram avaliadas em repouso, durante e após os treinos, enquanto as funções musculares foram avaliadas em repouso e durante a recuperação. O perfil bioenergético foi avaliado considerando as contribuições aeróbicas, anaeróbicas lácticas e anaeróbicas alácticas. A captura de movimento sem marcadores 3D foi utilizada para recolher dados durante o treino Isabel. A amplitude do componente rápido do $\dot{V}O_2$ foi maior no treino Isabel comparado com o treino Fran contínuo (42.0 vs $35.8 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$), contrário à constante de tempo (14.2 vs 23.7 s), cujos valores médios foram maiores no treino Fran contínuo, sem diferenças no atraso de tempo (4.3 vs 4.7 s , respetivamente) entre os treinos. O treino Fran contínuo provocou um maior pico de $\dot{V}O_2$, frequência cardíaca e contribuição aeróbica (62 vs 40 vs 41%) comparado com os treinos Isabel e Fran intermitente, que exibiram uma maior contribuição anaeróbica (38 vs 60 vs 59% , respetivamente). Foi observada uma redução na função muscular na capacidade de salto e no teste de prancha em posição prona durante a recuperação dos treinos Fran (intermitente e contínuo). Na intensidade extrema do treino Isabel, a velocidade e a potência máximas de levantamento diminuíram da fase inicial para a final, enquanto o tempo do levantamento até a barra cruzar o quadril e o ombro diminuiu progressivamente ao longo do treino. As diferenças mecânicas, de intensidade e de volume entre os modos de treino ao máximo esforço influenciam os perfis cardiorrespiratório e bioenergético. Esta análise forneceu novas percepções

para a seleção da prescrição de intensidade e recuperação para treinos de CrossFit® (e treino de força) realizados ao máximo esforço.

List of symbols and abbreviations

A₀	Oxygen uptake at rest
ANOVA	Analysis of variance
A_p	Amplitude of the fast oxygen uptake component
A_{sc}	Amplitude of the slow oxygen uptake component
Ana_{PCr}	Anaerobic alactic energy determined from PCr splitting in the contracting muscle
Ana_{recovery}	Anaerobic alactic energy determined from the fast component of the $\dot{V}O_2$ off kinetics
CI	Confidence interval
CO₂	Carbon dioxide
DBP	Diastolic blood pressure
e.g.	As example
EPOC	Excess post-exercise oxygen uptake
[Glu]	Blood glucose concentration
H	Heaviside step function
HR	Heart rate
HR_{max}	Maximal heart rate
HR_{peak}	Peak heart rate
[La⁻]	Blood lactate concentration
[La⁻]_{net}	Net accumulation of blood lactate concentration
M	Body mass
min	Minute
O₂	Oxygen
PCr	Phosphocreatine
s	Second
SD	Standard deviation
TD_p	Time delay of the fast oxygen uptake component
T_{sc}	Time delay of the slow oxygen uptake component
$\dot{V}O_2$	Oxygen uptake
$\dot{V}O_{2max}$	Maximal oxygen uptake
$\dot{V}O_{2peak}$	Peak oxygen uptake
T	Time
T_p	Time constant of the fast oxygen uptake component
T_{sc}	Time constant of the slow oxygen uptake component
RPE	Rating of perceived exertion
SBP	Systolic blood pressure
β	Constant for oxygen equivalent of blood lactate concentration net

Chapter 1 General introduction

Physical fitness benefits related to high-intensity exertion and a sense of community have led CrossFit® to an unprecedented level of global popularity (Claudino et al., 2018). According to the official CrossFit® website (crossfit.com), boxes are located in 142 countries across seven continents with more than 14,000 affiliates (Dominski et al., 2020; Schlegel et al., 2020). There is a great number of individuals performing this mode of physical exercise, from apparently healthy to even obese individuals, with 95% of participants aiming primarily to improve their general health status (Dominski et al., 2020; Schlegel et al., 2020). Like other high-intensity exercise modes, CrossFit® improves body composition, muscle strength and cardiorespiratory fitness (Falk et al., 2019; McDougale et al., 2023). However, a growing body of evidence indicates that physiological demands imposed by some CrossFit® workouts and/or the lack of appropriate recovery may place the participants at increased risk of overload, fatigue and injury, especially in poorly trained individuals (Meyer et al., 2017; Tibana & de Sousa, 2018).

CrossFit® workouts comprise high-intensity functional movements that are typically composed of gymnastic-type exercises, metabolic conditioning and weightlifting (Tibana & de Sousa, 2018). These exercise routines are performed in a circuit format, with little or no resting periods, with the goal of finishing in the best time possible or to achieve the highest number of repetitions/rounds over periods of 20-40 min (Rios et al., 2021). To assess fitness and monitor changes in work capacity, CrossFit® incorporates benchmark workouts (**Table 1**), with Cindy being the most extensively assessed (Kluszczewicz et al., 2017; Maté-Muñoz et al., 2018; Forte et al., 2022). The CrossFit® benchmark workouts adhere to standardized conditions, ensuring uniform performance comparisons among crossfitters worldwide (Meier et al., 2021). Some CrossFit® workouts elicit significant hormonal and metabolic disturbances, coupled with heightened oxidative stress and inflammation (Kluszczewicz et al., 2015; Poderoso et al., 2019; Rios et al., 2021). However, the intensity domain and the corresponding physiological (e.g. bioenergetics) and biomechanical (e.g. kinematics) responses elicited by many CrossFit® workouts remains unknown. These

aspects play a crucial role in determining the degree of fitness improvements achievable. Neglecting to comprehend these factors may heighten the risk of overloading the body, potentially leading to adverse outcomes (Tibana & de Sousa, 2018; Claudino et al., 2018).

CrossFit® benchmark workouts			
Exclusively bodyweight movements	Cindy As many rounds and repetitions as possible (for 20 min) Five pull-ups 10 push-ups 15 air squats	Chelsea One full round every min (for 30 min) Five pull-ups 10 push-ups 15 air squats	Barbara 5 rounds (for time) 20 pull-ups 30 push-ups 40 sit-ups 50 air squats
	Kelly Five rounds (for time) 400-m run 30 box jumps (24/20) 30 wall ball shots (20/14 lb)	Helen Three rounds (for Time) 400-m run 21 kettlebell swings 12 pull-ups	Eva Five rounds (for time) 800-m run 30 kettlebell swings 30 pull-ups
Incorporating bodyweight movements plus wall balls and/or kettlebell			
Incorporating a combination of barbell plus calisthenics movements	Fran 21-15-9 (repetitions for time) Thrusters (95/65 lb) Pull-ups	Jackie (for time) 1000-m row 50 thrusters (45/35 lb) 30 pull-ups	Amanda 9-7-5 (repetitions for time) Muscle-ups Squat snatches (135/95 lb)
	Isabel (for time) 30 snatches (135/95 lb)	Grace (for time) 30 clean and jerks (135/95 lb)	Linda 10-9-8-7-6-5-4-3-2-1 (repetitions for time) Deadlift (1½ bodyweight) Bench press (bodyweight) Clean (¾ bodyweight)
Intensive barbell workouts with heavy weights			

Table 1. A comprehensive overview of the exercises and structural elements inherent in CrossFit® benchmark workouts.

Indeed, the association between fatigue and biodynamic movements is especially important in the context of CrossFit® workouts. These workouts often incorporate technically challenging weightlifting exercises and utilize heavy loads, underscoring the importance of understanding how fatigue influences biomechanical movements. Addressing this relationship is essential for optimizing training strategies, minimizing injury risks, and enhancing performance outcomes in CrossFit® athletes (Tibana & de Sousa, 2018; Nicolay et al., 2022). The incidence of injuries in CrossFit® varies from 0.2-18.9 per 1,000 h of participation, a range comparable to other sports like as weightlifting and powerlifting (Feito et al., 2018; Klimek et al., 2018). Thus, it is necessary to reformulate certain workouts to ensure individuals can maintain movement quality effectively. Alternatively, such workouts might be best reserved for well-

conditioned individuals possessing advanced technical skills. In addition, there are marked variations in the exercises response and recovery period between males and females given sex-specific physiological differences (Weisenthal et al., 2014; Hottenrott et al., 2021). These physiological variations may contribute to sex differences in the adaptive response to high-intensity CrossFit® workout, as the acute response underpins the subsequent adaptations and outcome (Howden et al., 2015). Monitoring exercise load properly and considering sex-specific responses to training are essential for avoiding health issues and maximizing fitness.

A significant portion of CrossFit® workout-related research is dedicated to identifying predictive variables for performance through traditional laboratory tests (Bellar et al., 2015; Meier et al., 2021). Nevertheless, given its specificity, the use of traditional testing protocols is limited as the physiological demands differ from those in a real-world training context. Early research has highlighted a weak correlation between the predictive factors influencing performance in CrossFit® Fran workout and maximal treadmill aerobic capacity (Dexheimer et al., 2019; Zeitz et al., 2020). However, a direct correlation has been demonstrated with the anaerobic threshold obtained on a cycle ergometer (Butcher et al., 2015). The CrossFit® Isabel workout yields a significant power demand (when related with the full squat test), emphasizing anaerobic predominance in completing snatches (Peña et al., 2021). Advocating for standardized testing protocol may disregard the principle of sport specificity (Sandbakk et al., 2021) with only a limited number of cross-sectional studies that specifically investigate the real-world CrossFit® training context (Fernández et al., 2015; Tibana et al., 2018). This limitation underscores the urgency for additional studies aimed at unraveling the factors influencing CrossFit® performance.

It is widely acknowledged that physiological and biomechanical factors play a crucial role in enhancing sport performance across various types of exercises (Sousa et al., 2015; Borgonovo-Santos et al., 2021). Physiological factors manifest in the ability to generate mechanical work during physical exertion, a process determined by the muscle cells capacity to supply energy through integrated metabolic processes (Gastin, 2001). The study of oxygen uptake

($\dot{V}O_2$) kinetics involves delving into the physiological mechanisms responsible for the dynamic $\dot{V}O_2$ response to exercise (Whipp, 1990; Jones & Burnley, 2009). This process includes determining the instantaneous transfer of aerobic and anaerobic energy, the composition and quantity of substrate utilized, and the sustainable duration of exercise (Medbø & Tabata, 1989; Gastin, 2001; Reis et al., 2015). Biomechanical factors are predominantly focused on the analysis of movement, with a notable emphasis on kinematic and kinetic evaluations to assess movement technique (Schoenfeld, 2010; Thompson et al., 2023). Moreover, evaluating the degree of fatigue induced by these workouts and the subsequent recovery time will not only contribute to enhancing physical fitness and health-related gains, but also serve to safeguard crossfitters from potential overload and injury.

Evaluating $\dot{V}O_2$ kinetics at the onset of exercise provides valuable insights into the body's capacity to meet changing metabolic demands, shedding light on circulatory and metabolic responses during exercise (Poole & Jones, 2012). Traditionally, the dynamic $\dot{V}O_2$ response to exercise has been categorized into three intensity domains: low-moderate (up to the anaerobic threshold), heavy (above the anaerobic threshold) and severe (where maximal $\dot{V}O_2$ is achieved) domains (Gaesser & Poole, 1996; Pringle et al., 2003; Robergs, 2014). An extreme intensity domain has been proposed for performances leading to exhaustion before maximal $\dot{V}O_2$ is reached (Hill et al., 2002). In this intensity domain, $\dot{V}O_2$ kinetics are characterized by development of a fast component with insufficient time for the appearance of a discernible $\dot{V}O_2$ slow component (Monteiro et al., 2023). Studies have consistently reported a strong association between faster $\dot{V}O_2$ kinetics, reduced $\dot{V}O_2$ slow component amplitude, high levels of cardiorespiratory fitness, training status, and better tolerance to fatigue (Koppo et al., 2004; Krstrup et al., 2009). Notably, despite extensive assessments in running, cycling, swimming and rowing (Pringle et al., 2002; Jones et al., 2004; Sousa et al., 2015), there is a lack of evaluation of $\dot{V}O_2$ kinetics, cardiorespiratory function and metabolic responses during CrossFit® workouts.

Sustaining exercise beyond a few seconds relies on effective oxygen supply and utilization (Gastin, 2001) with $\dot{V}O_2$ measurement adequately assessing

overall energy expenditure at submaximal intensities (Ferretti et al., 2011; Zamparo et al., 2020). However, determining total energy expenditure becomes challenging at higher intensities when anaerobic contributions cannot be overlooked. Indeed, close to or above maximal $\dot{V}O_2$, a true steady state of $\dot{V}O_2$ is unattainable, with non-aerobic energy contributions playing a significant and influential role (Bertuzzi et al., 2013; Ribeiro et al., 2015). Neglecting these anaerobic contributions leads to underestimation of total energy expenditure, negatively impacting the understanding of performance in maximal all-out efforts of different durations (Reis et al., 2011; Zamparo et al., 2020). While metabolic contributions have been studied extensively in various cyclical exercise modes (di Prampero, 1986; Capelli, 1999; Sousa et al., 2015), there is a scarcity of research focusing on CrossFit® workouts in real-world contexts.

Understanding the intricate relationship between available energy and exercise-induced fatigue holds particular significance in the context of CrossFit® training. The risk of early fatigue, heightened perception of effort and compromised movement execution escalates with an excess in volume loads and an increased number of training sessions (Claudino et al., 2018; Cooper et al., 2020). Crossfitters often report elevated feelings of excessive fatigue, muscle soreness, swelling, shortness of breath, muscle pain to light touch, and restricted movement within 24-48 h post-workout (Wang & Cheng, 2020; Sousa Neto et al., 2022). The fixed external loads set for CrossFit® workouts (e.g. 43 kg for Fran and 61 kg for Isabel in males) significantly impact the kinematics and kinetics of biodynamic movements with the imposition of additional loads on the knee, hip and shoulders amplifies the susceptibility to injuries (Montalvo et al., 2017; Tibana & de Sousa, 2018). It is crucial to analyze variations in technical execution as fatigue progresses, providing valuable insights for researchers and coaches (Jiménez-Reyes et al., 2023). Moreover, comprehending the time-course of recovery following CrossFit® session is important for minimizing the risk of maladaptation due to insufficient recovery between each stimulus, and would inform optimal exercise monitoring (Tibana et al., 2018; Sousa Neto et al., 2022).

The focus of the thesis is assessment and characterization of the physiological and biomechanical aspects of Fran and Isabel CrossFit® benchmark workouts.

The experimental details are presented in Chapters 2 to 7, followed by a comprehensive discussion in Chapter 8. Finally, the main conclusions, suggestions for future research and the highlighter for references section are presented in Chapters 9, 10 and 11 (respectively). A more detailed description of the experimental studies will now be addressed.

Among the CrossFit® workouts studied in this thesis, the Fran workout was the most explored. Although the advent of portable automated and lighter breath-by-breath gas-analysis systems has led to more sustained and reliable bioenergetic research (Tabata et al., 1996; Sousa et al., 2015), CrossFit® workouts have not previously assumed a prominent role in the energetics of human locomotion literature (Zamparo et al., 2020). Thus, the first purpose was to conduct a detailed physiological assessment of each round of the Fran workout performed intermittently, i.e. with 30 s rest in between rounds. In addition, the degree of post-workout fatigue was evaluated, and whether the duration and high-intensity workout reduces muscle functionality. We hypothesized that Fran workout would primarily rely on the anaerobic system and this high-intensity, short-duration exercise would evoke a significant reduction in muscle functionality (**Chapter 2**).

The magnitude and nature of the adjustment in $\dot{V}O_2$ kinetics at the onset of any exercise strongly depends on the intensity and mode in which it is performed (Jones & Burley, 2009). In addition, specific energy inputs and the corresponding recovery of muscle functionality can be influenced by intervals during exercise (Medbø & Tabata, 1989; Tabata et al., 199). Thus, for a comprehensive understanding of Fran's unbroken workout, we presented a study which analyzed $\dot{V}O_2$ kinetics and the contribution of each energy system to Fran workout performed at maximum effort in **Chapter 3**. We also evaluated post-Fran workout fatigue and recovery time. We hypothesized that unbroken Fran workout imposes specific cardiorespiratory demands consistent with the domain of severe intensity, highlighting a significant contribution from the aerobic energy pathway, even in brief, highly intense CrossFit® workouts.

The bioenergetic characterization of any exercise mode is fundamentally shaped by the muscle cells capacity to generate energy through two distinct yet

interlinked pathways: aerobic and anaerobic (Gastin, 2001). While the lactic anaerobic contribution has been extensively studied, the alactic system has received less attention, often being assessed based on the decline in phosphocreatine concentration during the transition from rest to exhaustion in active muscle mass (Zamparo et al., 2011). While it has faced criticism for relying on certain assumptions, an alternative approach involves analyzing the fast component of the $\dot{V}O_2$ off-kinetics curve (Margaria et al., 1933; Zamparo et al., 2020). In **Chapter 4** we determined and compared the contribution of the alactic system at the Fran workout on maximal effort using the two methods.

Physiological factors influence differences in physical fitness and performance between males and females, stemming from distinct strength and endurance predispositions (Howden et al., 2015; Coe et al., 2023). Males compared to females, exhibit a greater heart size, blood volume and hemoglobin mass, resulting in a 10% higher maximal $\dot{V}O_2$ (Howden et al., 2015). In addition, sex differences in oxidative capacity and resistance to fatigue are also evident, possibly linked to a reduced reliance on nonoxidative metabolism during exercise in females (Astorino et al., 2022). Given the growing popularity of CrossFit® among both sexes, it is crucial to explore potential differences in these physiological responses (e.g. cardiorespiratory, hemodynamic and metabolic), contributing to a better understanding of CrossFit® workouts and to optimal exercise recommendations. Thus, the aim of **Chapter 5** was to extend the previous physiological findings from Chapters 2 and 3 by comparing cardiorespiratory, hemodynamic and metabolic responses between sexes, to verify the degree of contrasting acute adaptations to the Fran workout. The hypothesis was that Fran workout is aligned with the guidelines for enhancing cardiorespiratory fitness, and that males would exhibit higher $\dot{V}O_2$ and heart rate (HR) levels than females.

At extreme intensity events lasting approximately 2 min, the overall energy expenditure encompasses the cumulative rates of oxidative phosphorylation, anaerobic glycolysis (resulting in lactate production) and creatine phosphate splitting (Tabata et al., 1996; Gastin, 2001). Studies that overlook the contribution of oxygen-independent metabolism, specifically the glycolytic and phosphagen pathways, at elevated exercise intensities may underestimate total

energy expenditure, affecting the comprehensive understanding of the effects of the workout. Furthermore, it has been proposed that, even in short-duration cyclic exercise modes, there is a significant aerobic energy contribution (Sousa et al., 2015; Zamparo et al., 2020). This premise underscores the importance of analyzing the $\dot{V}O_2$ kinetics (by modeling $\dot{V}O_2$ response) and neglecting to consider these factors could hinder a thorough comprehension of the metabolic demands and physiological responses associated with extreme intensity short-duration exercise. Hence, the purpose of **Chapter 6** was to assess the $\dot{V}O_2$ kinetics, the contribution of different energy systems, and quantify the total energy expenditure of Isabel workout performed in the extreme intensity domain. We hypothesized that the specific cardiorespiratory demands of this well-known landmark would be consistent with the extreme intensity domain classification.

After identifying the physiological factors and energy profiles of Isabel workout, we deemed it pertinent to thoroughly characterize its potential biomechanical changes. To achieve this goal, we conducted an analysis of kinematics and kinetics factors throughout the Isabel workout performed at maximal effort, focusing particularly on changes in knee, hip and shoulders angles (**Chapter 7**). We anticipated elevated velocity and power in the initial segment, followed by a gradual decrease in subsequent repetitions, coupled with a reduction in knee and hip angles.

Then, in **Chapter 8**, a comprehensive discussion is provided, outlining the outcomes, insights and practical applications of the thesis, and contrasting them with the literature and contemporary practices in the field. The contribution of the research to addressing gaps in knowledge regarding CrossFit® workouts (and strength training) applications, and potential avenues for further improvement are analyzed. Final considerations and conclusions are addressed in **Chapter 9**, with recommendations for future research presented in **Chapter 10**. The respective bibliographic references supporting each aspect of the work are listed in the **Chapter 11**.

Chapter 2

Bioenergetic analysis and fatigue assessment during the Fran workout in experienced crossfitters

Manoel Rios,^{1,2} Rodrigo Zacca,^{3,4} Rui Azevedo,⁵ Pedro Fonseca,² David B. Pyne,⁶ Victor Machado Reis,^{7,8} Daniel Moreira-Gonçalves,^{3,4} and Ricardo J. Fernandes^{1,2}

¹Center of Research, Education, Innovation and Intervention in Sport, Faculty of Sport, University of Porto, Porto, Portugal

²Porto Biomechanics Laboratory, Faculty of Sport, University of Porto, Porto, Portugal

³Research Center in Physical Activity, Health and Leisure, Faculty of Sport, University of Porto, Portugal

⁴Laboratory for Integrative and Translational Research in Population Health, Porto, Portugal

⁵Toxicology Research Unit, University Institute of Health Sciences, CESPU CRL, 4585-116 Gandra, Portugal

⁶Research Institute for Sport & Exercise, University of Canberra, Canberra, Australia

⁷Department of Sport Sciences, Exercise and Health, University of Trás-os-Montes e Alto Douro, Vila Real, Portugal

⁸Research Center in Sports Sciences, Health Sciences and Human Development, Vila Real, Portugal

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Abstract

To quantify the physiological demands and impact of muscle function of the Fran workout, one of the most popular CrossFit® benchmarks. Twenty experienced crossfitters —16 male: 29 (6) years old and 4 female: 26 (5) years old—performed 3 rounds (with 30-s rests in between) of 21–21, 15–15, and 9–9 front squats to overhead press plus pull-up repetitions. Oxygen uptake and heart rate were measured at baseline, during the workout, and in the recovery period. Rating of perceived exertion, blood lactate, and glucose concentrations were assessed at rest, during the intervals, and in the recovery period. Muscular fatigue was also monitored at rest and at 5 min, 30 min, and 24 h post-exercise. Repeated-measures analysis of variance was performed to compare time points. Aerobic (52%–29%) and anaerobic alactic (30%–23%) energy contributions decreased and the anaerobic lactic contribution increased (18%–48%) across the 3 rounds of the Fran workout. Countermovement jump height decreased by 8% (–12 to –3) mean change (95% CI), flight duration by 14% (–19 to –7), maximum velocity by 3% (–5 to –0.1), peak force 4% (–7 to –0.1), and physical performance (plank prone 47% [–54 to –38]) were observed. It appears that the Fran workout is a physically demanding activity that recruits energy from both aerobic and anaerobic systems. This severe-intensity workout evokes substantial post-exercise fatigue and corresponding reduction in muscle function.

Key words: high-intensity exercise; energetics; physical fitness

Introduction

CrossFit® training combines weightlifting, gymnastics and traditional cardiovascular exercises (e.g. rowing and air bike) into a single high intensity workout (Rios et al., 2021; Schlegel, 2020). This form of training engages thousands of participants around the world, training a wide range of routines (Claudino et al., 2018; Schlegel, 2020). The daily workouts vary on exercise modality, intensity and/or volume to induce specific metabolic and mechanical adaptations aiming to increase physical fitness (Claudino et al., 2018; Liguori & Medicine, 2020). The overall workout performance is typically assessed by the time to complete it or simply by the number of repetitions (Claudino et al., 2018; Rios et al., 2021), with most well-known ones (like Fran and Grace) being also used for physical fitness and performance assessment (Liguori & Medicine, 2020; Mangan et al., 2018).

Fran is one of the most popular CrossFit® benchmarks, a time-scored workout consisting of three rounds of 21-21, 15-15 and 9-9 front squat to press overhead (using a 43 and 30 kg barbell for males and females, respectively) plus pull-ups repetitions (Mangan et al., 2018). High values of heart rate (HR), blood lactate concentration ($[La^-]$) and rating of perceived exertion (RPE) have been reported (Butcher et al., 2015; Leitão et al., 2021; Tibana et al., 2018), and moderate relationships between the anaerobic threshold (obtained on a cycle ergometer) and back squat strength were observed (Butcher et al., 2015; Dexheimer et al., 2019; Leitão et al., 2021). However, the intermittent nature of the Fran workout, involving transitioning between front squat to press overhead plus pull-ups repetitions, may be influenced by the participants anaerobic potential and recover ability (Chamari & Padulo, 2015; Hargreaves & Spriet, 2020). Thus, the anaerobic capacity and tolerance, as well as the aerobic power, are major likely determinates of Fran's workout performance (Hargreaves & Spriet, 2020; Tabata et al., 1997).

Since exercise energy expenditure is derived from both aerobic and/or anaerobic (lactic plus alactic) energy pathways, physical training enhances metabolic efficiency and sport performance (Di Prampero, 1986; Tabata et al., 1997). Metabolic contributions have been estimated for several exercise modes,

such as surfing, swimming, cycling, running and rowing (Borgonovo-Santos et al., 2021; Sousa et al., 2015; Zacca et al., 2020), but few studies have examined CrossFit® (Butcher et al., 2015; Leitão et al., 2021) and none specifically with the Fran workout. The associations between the energy available and the exercise induced fatigue, particularly important during CrossFit® workouts, should be better understood, helping coaches and researchers optimize the training process and routines (Maté-Muñoz et al., 2018; Timón et al., 2019).

Despite the recent increase in the number of CrossFit®-related scientific publications and its great popularity, scientific knowledge is still incipient in this sport, so more studies are required for accomplishing a deeper knowledge on the topic. The aim of study was to quantify the energy contribution of the CrossFit® workout Fran, and evaluate whether it is mainly supported by the anaerobic system (as expected) over a typical ~100-250 s duration (Mangine et al., 2018). We also assessed the degree of post-exercise fatigue and determined whether this short duration high intensity workout yields a marked reduction in muscle functionality.

Methods

Participants

Twenty experienced crossfitters (n = 16 males and 4 females) with 28.9 (5.9) and 25.5 (5.3) years old, 79.0 (8.3) and 64.5 (0.6) kg of body mass, 175.4 (5.4) and 160.5 (3.9) cm of height, 25.6 (1.7) and 25.1 (1.3) kg·m⁻² of body mass index, and 5.6 (1.7) and 5.8 (2.2) years of CrossFit® training experience (respectively) volunteered to participate in the study. crossfitters were recruited by detailed announcements at local CrossFit® affiliate gyms according to the following inclusion criteria: (1) >3 years of CrossFit® practice, (2) regular participation in regional or national competitions, (3) not presenting with any physical impairments, (4) between 18 and 40 years of age, and (5) being free to exercise according to the Physical Activity Readiness-Questionnaire. Before the testing session, participants were informed about the experiment's procedures, benefits, and potential risks. The study was approved by the local research

ethics committee (CEFADE 21—2019) and followed the Declaration of Helsinki and guidelines of the World Medical Association for research with humans.

Experimental design

Following a cross-sectional design, each experienced crossfitter underwent 2 evaluation days under the same environmental conditions (20 °C ambient temperature, 60% humidity, and between 8 AM and 12 AM). All tests were performed in the same laboratory facility and supervised by one experienced researcher. In the first session, after 10 min of joint mobility warm-up and the Fran workout's specific exercises with low loads, each crossfitter performed the Fran workout at maximal exertion (Figure 1). Oxygen uptake ($\dot{V}O_2$) and HR were evaluated continuously and $[La^-]$, blood glucose ($[Glu]$), and RPE assessed during the 30 s intervals between rounds. $\dot{V}O_2$, HR, $[La^-]$, $[Glu]$, session RPE, and self-reported muscular fatigue responses were also measured at rest and 3 min, 5 min, and 30 min after the workout end. The second session occurred 24 h after and assessed muscular fatigue, with crossfitters performing the countermovement jump and a prone plank test. Participants were instructed to maintain their normal nutritional habits and abstain from exhaustive exercise for 48 h before data collection and during the evaluation period.

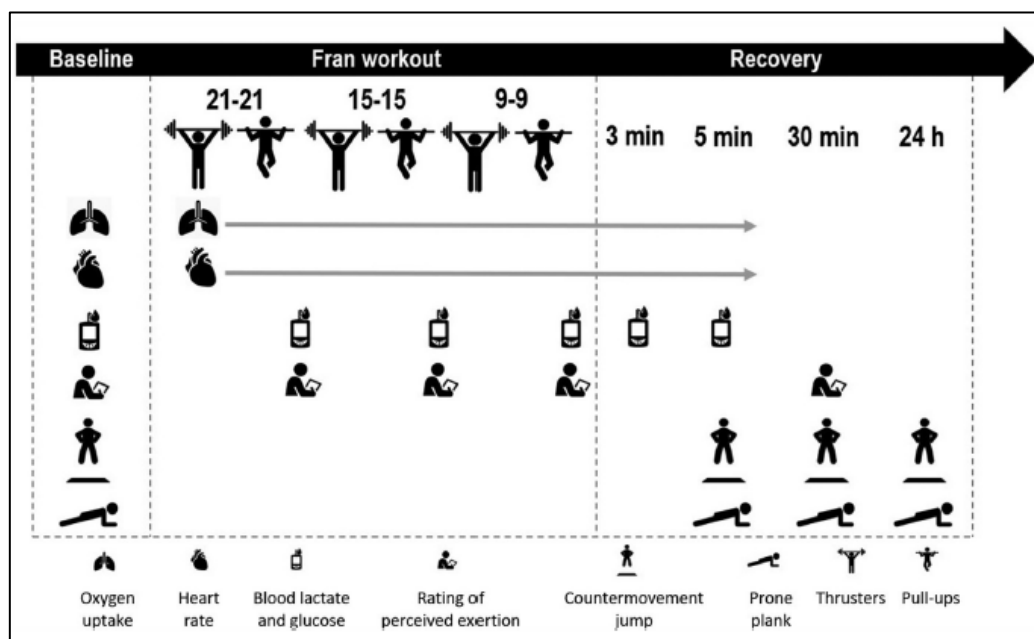


Figure 1. Data-collection setup for the Fran workout.

Methodology

Body mass and height were obtained before the experimental session using a digital scale with a built-in stadiometer (SECA, model 220). Body mass index was calculated by dividing body mass by height squared. Capillary blood samples (5 μ L) for $[La^-]$ and $[Glu]$ concentration assessments were collected from an earlobe at baseline, during the 30 s intervals between rounds, and immediately after the exercise (at the first, third, and fifth minutes) using a Lactate Pro (Arkay, Inc) and Accu-Chek Aviva analyzer (respectively). The 6 to 20 Borg scale was used to assess RPE and session RPE at baseline, after each round, and 30 min post-workout (respectively). Pulmonary gas exchange was measured breath-by-breath at rest, during exercise, and post-exercise using a K4b2 telemetric portable gas analyzer (Cosmed). HR was also registered continuously by a Polar T34 Heart Rate Transmitter (Polar) that telemetrically sent the data to the K4b2 portable unit.

The accumulated $\dot{V}O_2$ values during each round, and for the complete Fran workout, were calculated from the time integral of the net $\dot{V}O_2$ versus time exercise duration relationship (Medbø & Tabata, 1989; Tabata et al., 1997). The highest $\dot{V}O_2$ value per round was defined as its $\dot{V}O_{2peak}$. The post-exercise oxygen (EPOC) was estimated by subtracting the area under resting $\dot{V}O_2$ from the area under the recovery $\dot{V}O_2$ curve (biexponential fit, as in the equation below):

$$\dot{V}O_2(t) = A_0 - H(t - T_{D_p}) A_p (1 - e^{-(t - T_{D_p})/T_p}) - H(t - T_{D_{sc}}) A_{sc} (1 - e^{-(t - T_{D_{sc}})/T_{sc}})$$

where $\dot{V}O_2(t)$ represents the relative $\dot{V}O_2$ at the time t , A_0 is the $\dot{V}O_2$ at rest, H represents the Heaviside step function (Ma et al., 2010), A_p and A_{sc} , T_p and T_{sc} , T_{D_p} and T_{sc} are the amplitude, time constant and time delay of the $\dot{V}O_2$ fast and slow components, respectively (Zacca et al., 2019). The $VO_2FITTING$ software (Zacca et al., 2019) was used for data analysis and treatment, as well as for editing and modelling each individual $\dot{V}O_2$ response. Energy expenditure was calculated as the sum of anaerobic alactic, anaerobic lactic and aerobic energy pathways (Di Prampero, 1986; Zacca et al., 2020; Zamparo et al., 2020). Anaerobic alactic contribution was estimated from the maximal phosphocreatine

splitting in the contracting muscle using the following equation (Sousa et al., 2015; Zamparo et al., 2011):

$$\text{Anaerobic alactic} = \text{PCr} \cdot (1 - e^{-t/\tau}) \cdot M$$

where PCr is the phosphocreatine concentration at rest, t is the exercise time, τ is the time constant of the PCr splitting at exercise onset (23.4 s) and M (kg) is the body mass. Subsequently, this estimate was expressed in kJ by assuming an energy equivalent of $0.468 \text{ kJ} \cdot \text{mM}^{-1}$ and a phosphate/oxygen ratio of 6.25 (Sousa et al., 2015; Zamparo et al., 2011). Anaerobic lactic contribution was obtained using the following equation (Di Prampero, 1986; Sousa et al., 2015):

$$\text{Anaerobic lactic} = [\text{La}^-]_{\text{net}} \cdot \beta \cdot M$$

where $[\text{La}^-]_{\text{net}}$ is the difference between the $[\text{La}^-]$ at baseline and after each round, β is the constant for O_2 equivalent of $[\text{La}^-]_{\text{net}}$ ($3 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{mM}^{-1}$) and M (kg) is the body mass (Sousa et al., 2015; Zacca et al., 2020). To determine the aerobic energy contribution, the time integral of the net $\dot{\text{V}}\text{O}_2$ versus time relationship was calculated, with energy system contributions expressed in kJ by assuming an energy equivalent of $20.9 \text{ kJ} \cdot \text{L}^{-1}$ (Sousa et al., 2015; Zamparo et al., 2011). Metabolic power was estimated as the ratio between energy expenditure and time (Sousa et al., 2015; Zamparo et al., 2011), and caloric expenditure estimated by multiplying absolute $\dot{\text{V}}\text{O}_2$ by $5.05 \text{ kcal} \cdot \text{L}^{-1}$ and expressed in kJ by assuming an energy equivalent of $4.184 \text{ kJ} \cdot \text{L}^{-1}$ (Ratamess et al., 2015; Reis et al., 2019).

The countermovement jump test was performed on a OR6-WP portable force platform (AMTI, Watertown, USA) and initiated with the lower limbs extended and hands on the hips. The lower limbs were then flexed to 90° and explosively extended in a coordinated manner aiming for maximum height (Linthorne, 2001). Participants undertook three jumps (with 30 s intervals), with the best trial used to calculate flight duration, maximum height, peak force and maximum velocity values (Linthorne, 2001; Rago et al., 2018). These variables were calculated from the force-time and velocity-time curves using a custom-made MATLAB R2020b routine (MATLAB, MathWorks, Natick, MA, USA). In the prone plank test, a chronometer (Seiko, Tokyo, Japan) was used to measure

the time participants were able to maintain the position with toes and forearms supporting the body mass (Timón et al., 2019).

Statistical analysis

Assuming a statistical power (β) of 0.80, a moderate effect size (0.25), and an overall level of significance of 0.05, a sample size of 20 participants proved adequate for conducting the study (G*Power 3.1.9.7). All statistical calculations were completed using GraphPad Prism 6 (GraphPad Software), with mean and standard deviation values for descriptive analysis reported for all variables. The Shapiro–Wilk test was used to assess data normality. Repeated-measures analysis of variance (with a Bonferroni post hoc test) was applied to compare the Fran workout performance-, cardiorespiratory-, metabolic-, energetic-, and fatigue-related variables at different time points. The 95% confidence interval (95% CI) was also calculated with the significance level set at 5%.

Results

The Fran workout performance and physiological variables are reported in Table 1. Exercise duration decreased from the first to the last round, while exercise frequency was constant at the first 2 rounds (decreasing at the third round). Accumulated and peak $\dot{V}O_2$ values decreased along the workout, and mean and peak HR values were similar during the exercise and higher than baseline. Perceived exertion, $[La^-]$, lactatemia net, rate of blood $[La^-]$ appearance, and $[Glu]$ levels increased progressively along the workout, with the highest values observed at third round. The absolute aerobic and anaerobic energy contributions were similar at the first round, while aerobic contributions gradually decreased and anaerobic contributions progressively increased in the latter rounds. The anaerobic alactic contribution was highest in the first round, decreasing along the workout.

The total energy expenditure was lower at the first round than the last 2 rounds even with considerably higher duration (Table 1). Metabolic power was also lower at the first round than the last 2, with the second round lower than the third. In contrast, caloric expenditure was higher in the first round compared with the third. At 5 min post-workout, EPOC, $[La^-]$, $[Glu]$, and caloric

expenditure values were higher compared to baseline and, inclusively, to the workout values (with the highest $[La^-]$ and $[Glu]$ values observed in the third minute of recovery). The crossfitters' session RPE was 15 ± 2 (95% CI, 14–16) at 30 min of recovery, which was higher than the baseline and the first-round values.

Variable	Baseline	Round 1	Round 2	Round 3	Total workout	Recovery 3 min	Recovery 5 min
Duration (s)	---	82 (10) [78–86]	63 (8) # [59–67]	44 (9) # + [40–48]	189 (19) [178–200]	---	---
Exercise frequency (repetition/s)	---	0.5 (0.1) [0.5–0.5]	0.5 (0.1) [0.4–0.5]	0.4 (0.1) # + [0.4–0.5]	0.5 (0.1) [0.5–0.5]	---	---
Accumulated oxygen uptake (L·min ⁻¹)	0.5 (0.1) [0.5–0.5]	2.7 (0.6) * [2.4–2.9]	2.4 (0.5) * # [2.1–2.6]	1.7 (0.4) * # + [1.5–1.8]	6.8 (2.2) [5.7–7.7]	---	4.2 (1.1) * # + § [3.7–4.7]
Peak oxygen uptake (mL·kg ⁻¹ ·min ⁻¹)	---	46.1 (4.7) [43.8–48.2]	43.8 (4.8) # [41.6–46.0]	41.9 (4.4) # + [39.9–43.9]	---	---	---
Mean heart rate (b·min ⁻¹)	84 (9) [77–89]	174 (8) * [169–177]	174 (8) * [170–177]	175 (8) * [171–178]	174 (8) [170–181]	---	129 (9) * # + § [123–134]
Peak heart rate (b·min ⁻¹)	---	179 (7) [175–181]	180 (5) [178–182]	180 (4) [178–182]	---	---	---
Rating of perceived exertion (6–20 scale)	6 [6–6]	14 (2) * [13–15]	15 (2) * # [14–16]	16 (2) * # + [15–17]	---	---	---
Blood lactate (mmol·L ⁻¹)	1.6 (0.5) [1.3–1.8]	5.5 (1.2) * [4.8–6.0]	10.1 (2.5) * # [8.9–11.1]	13.7 (3.2) * # + [12.1–14.5]	---	15.6 (3.1) * # + § [14.1–17.0]	14.3 (3.4) * # + £ [13.0–15.8]
Lactatemia net (mmol·L ⁻¹)	---	3.9 (1.4) [3.2–4.5]	8.5 (2.5) # [7.3–9.6]	12.1 (3.4) # + [10.5–13.6]	13.2 (3.3) [11.6–14.7]	---	---
Rate of blood lactate appearance [(mmol·L ⁻¹) · s ⁻¹]	---	0.07 (0.02) [0.05–0.07]	0.16 (0.04) # [0.14–0.17]	0.32 (0.07) # + [0.28–0.35]	---	---	---
Blood glucose (mg·dL ⁻¹)	94 (7) [90–97]	106 (14) * [99–112]	114 (16) * # [107–121]	120 (15) * # + [113–126]	---	136 (18) * # + § [127–144]	132 (17) * # + § £ [123–138]
Aerobic energy (kJ)	---	54.0 (10.7) [48.9–59.0]	50.2 (9.9) # [45.5–54.8]	34.4 (8.1) # + [30.6–38.1]	138.6 (26.3) [126.2–150.9]	---	---
Lactic anaerobic energy (kJ)	---	18.3 (7.0) [15.0–221.5]	40.2 (14.2) # [33.5–46.8]	57.2 (19.0) # + [48.3–66.1]	115.7 (37.2) [98.2–133.1]	---	---
Alactic anaerobic energy (kJ)	---	30.5 (4.1) [28.5–32.3]	29.3 (4.1) # [27.3–31.2]	26.3 (4.4) # + [24.2–28.3]	86.1 (12.4) [80.2–91.8]	---	---
Total energy expenditure (kJ)	---	102.8 (15.3) [95.5–110.0]	119.6 (23.1) # [108.8–130.4]	117.9 (28.9) # [104.4–131.4]	340.3 (63.2) [310.7–369]	---	---
Metabolic power (kW)	---	1.3 (0.2) [1.1–1.3]	1.9 (0.3) # [1.7–2.0]	2.7 (0.5) # + [2.5–2.9]	1.8 (0.3) [1.6–1.9]	---	---
Caloric expenditure (kJ)	---	57 (12) [52–63]	50 (10) [45–55]	35 (8) # + [31–39]	143 (45) [121–164]	---	89 (22) # + § [78–99]

Data are presented as mean (SD) [95% CI]. * Different from baseline ($P \leq .05$). # Different from round 1 ($P \leq .05$). + Different from round 2 ($P \leq .05$). §

Different from round 3 ($P \leq .05$). £ Different from minute 3 of recovery period ($P \leq .05$).

The relative energy contribution values (per round and for the total workout) are presented in Figure 2. The aerobic contribution decreased from the first (52% [49–55], respectively mean [95% CI]) to the second (42% [39–44]) and third rounds (29% [27–30]), with a higher anaerobic lactic contribution from the second (33% [29–36]) to the third round (48% [45–50]) than the first round (18% [15–20]), and the anaerobic alactic contribution decreasing along the workout (30% [28–31], 25% [23–26], and 23% [21–24], respectively). Overall, the Fran workout is primarily dependent on the anaerobic component.

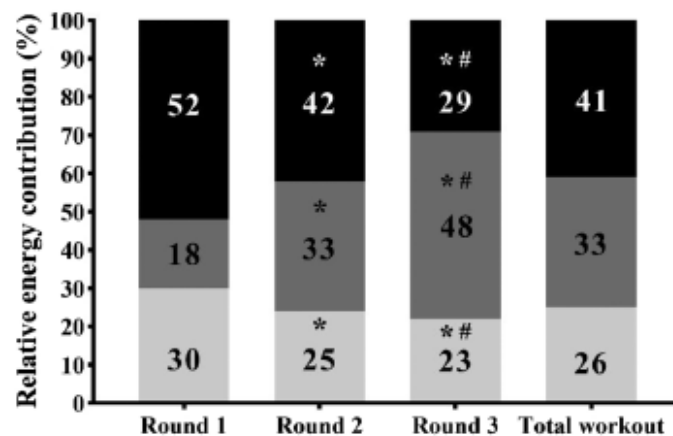


Figure 2. Fran workout relative aerobic, anaerobic lactic, and anaerobic alactic (black, dark gray, and light gray) energy contributions (per round and for the total workout). * Different from round 1 ($P \leq .05$). # Different from round 2 ($P \leq .05$).

The post-exercise muscular function values displayed in Figure 3 indicate that: (1) the jump height decreased at 5 and 30 min of recovery (-8% [-12 to -3] and -7% [-12 to -1], respectively, mean [95% CI]); (2) the flight duration decreased over the recovery 24 h compared with baseline, presenting higher values at 30 min and 24 h compared to 5 min of post-exercise (-14% [-19 to -7], -8% [-13 to -2], and -5% [-8 to -2], respectively); and (3) the maximum velocity and peak force decreased at 5 min of recovery (-3% [-5 to -0.1] and -4% [-7 to -0.1], respectively). However, the values maintained stable throughout the recovery period, and (4) the plank prone performance decreased at post-exercise 5 and 30 min, and 24 h; an increase was observed in 30 min and 24 h when compared to 5 min after a workout (-47% [-54 to -38], -29% [-38 to -20], and -10% [-17 to -1], respectively).

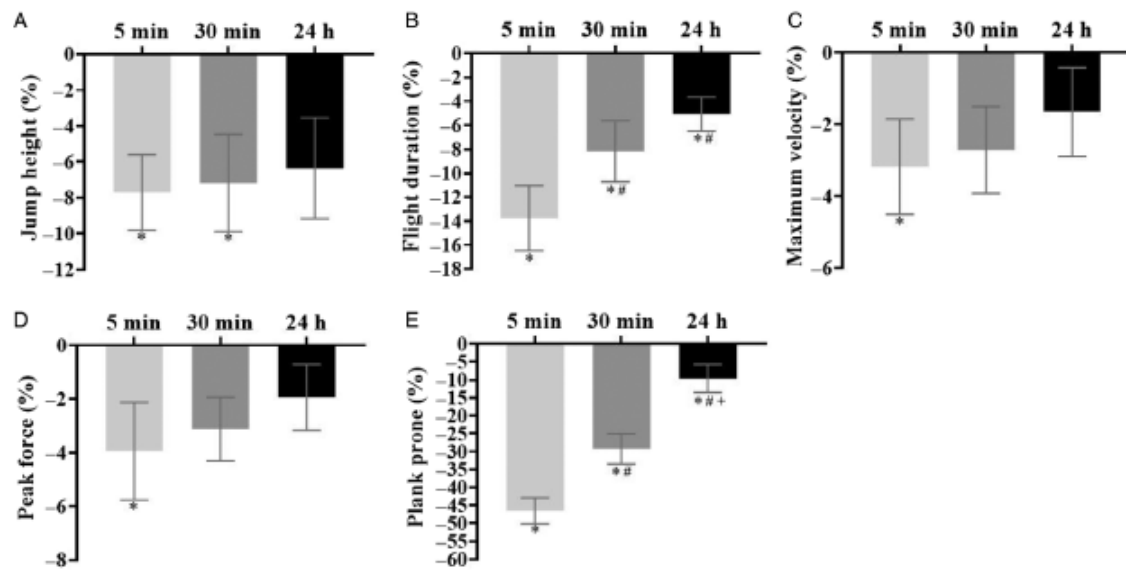


Figure 3. Muscular function variables obtained at the post-workout recovery period. Data are presented as mean (SD). * Different from baseline ($P \leq .05$). # Different from 5 min of recovery ($P \leq .05$). + Different from 30 min of recovery ($P \leq .05$).

Discussion

The purpose of the study was to undertake a deep bioenergetic and physiological characterization of the Fran CrossFit® workout by assessing the energy systems' contributions associated with each of the 3 rounds of exercise. Our results indicate that the 3 rounds that compose the Fran workout are highly demanding and supported by both energy systems (with a predominance of the anaerobic component, that is ~59% in overall performance). Moreover, the Fran routine elicits substantial reduction in muscle function associated with fatigue. Taken together, we conclude that the Fran workout is highly demanding and likely to stimulate substantial physiological and performance adaptations. These findings support the hypothesis that the Fran workout depends primarily on the metabolic anaerobic component and that, as a consequence of cumulative fatigue, complete body recovery may take longer than 24 h.

A decrease in exercise frequency was observed in the third round of the Fran workout, reflecting a reduction in muscle function (Smilios et al., 2010). The increase in $[La^-]$, $[Glu]$ and mean and peak HR during and after the Fran workout, as well as the elevated RPE values, indicates a severe intensity

exercise level when performing this routine (Leitão et al., 2021; Tibana et al., 2018). The $[La^-]$ and $[Glu]$ values increased in the third and fifth min of the recovery, possibly due to an increase in the anaerobic lactic contribution between rounds leading to greater involvement of carbohydrate metabolism. These effects would presumably reflect a greater amount of $[Glu]$ at the muscle level (Gastin, 2001; Timón et al., 2019). The accumulated and peak $\dot{V}O_2$ fluctuations from round to round could be explained by the decrease in the exercise duration and by the 30 s rest periods in-between, with phosphocreatine stores being refilled progressively (Gastin, 2001; Rogatzki et al., 2014). Peripheral arterial vessels of working muscles are compressed during severe-resistance exercise, which may affect muscle perfusion and gas exchange (Buitrago et al., 2013). The observed EPOC value is related to the workout intensity and muscle contraction velocity along the rounds that also resulted in higher metabolic stress (evidenced by the $[La^-]$ and $[Glu]$ values), ultimately affecting the return to homeostasis (Da Silva et al., 2010; Vianna et al., 2014).

The estimated energy contributions are in line with those of others studies of ~40-200 s efforts and their lower contribution across rounds was also associated with a decrease in exercise duration (Gastin, 2001). As O_2 availability is diminished during exercise, the amount of energy provided by anaerobic metabolism to maintain muscle contraction increases (Gastin, 2001; Sousa et al., 2015). In support of this assertion, the increased anaerobic lactic contribution could be attributed to the net $[La^-]$ accumulation along the routine ($1.6-12.1 \text{ mmol}\cdot\text{L}^{-1}$), expressing the increased recruitment of type II fibers needed to complete the workout (Sousa et al., 2015; Sousa Neto et al., 2022). In contrast, after a period of severe intensity exercise followed by short duration intervals (e.g. 30 s), phosphocreatine concentrations remain decreased and may not be restored at the beginning of the subsequent round, lowering the alactic anaerobic energy system contribution (Harris et al., 1977; Rodrigues-Krause et al., 2020). The methods by which the energy release is determined can have a substantial influence on calculation of the relative contribution of each energy system during periods of maximal effort exercise (Gastin, 2001; Sousa et al., 2015). An increase in total energy expenditure and metabolic power was observed over the workout course, indicative of an increasing

energy demand for completion of severe intensity actions (Da Silva et al., 2010; Zacca et al., 2020). The reduction in caloric expenditure during the Fran workout can be attributed to the volume and duration of the Fran rounds, while the increase in the recovery period is associated with an increase in $\dot{V}O_2$ (evidenced by the EPOC) during the return to homeostasis (Ratamess et al., 2015; Vianna et al., 2014).

We demonstrated that the Fran workout markedly impaired countermovement jumping ability, probably related to the increase in muscle acidosis ($1.6\text{-}15.6\text{ mmol}\cdot\text{L}^{-1}$) and reduction of phosphocreatine (30-23%) affecting muscle contractile capacity (Maté-Muñoz et al., 2018; Smilios et al., 2010). In support of this assertion, a reduction in countermovement jump height, duration, velocity and force was observed at 5- and 30-min post-workout. The 24 h post-workout muscle functionality failed to return to baseline, indicating that the crossfitters were not fully recovered. In fact, maximal exertion exercise impair muscle type fibers II prolonging the time of recovery (Halsen, 2014; Sousa Neto et al., 2022). Furthermore, we observed decreases in the plank test throughout the recovery period. Since the core muscles are the center of most body kinetic chains, and transfer forces to the extremities (Shinkle et al., 2012), the 90 repetitions of thrusters plus pull ups (closed kinetic chain exercises) clearly caused fatigue in this muscle group. This outcome had a negative effect since core muscles stability and activation are essential for achieving high scores in the plank test (Shinkle et al., 2012; Timón et al., 2019).

Conclusions

This is the first study to detail the physiological demands and impact on muscle function of the widely used Fran workout in experienced crossfitters. Elevated metabolic responses indicate that Fran is a severe-intensity workout. CrossFit® training should be monitored and adjusted according to individual requirements and specific energy demands, thereby optimizing recovery and minimizing the risk of injury. Future studies should evaluate the impact of a Fran workout without breaks between rounds to clarify the bioenergetics of the entire routine and post-workout muscle functionality. These studies should focus on $\dot{V}O_2$

behavior, characterize the intensity domain of this workout, and evaluate technical modifications during a CrossFit® Fran workout.

Practical Applications

We have identified some important characteristics of the Fran workout, a popular CrossFit® benchmark. Coaches and crossfitters should recognize the metabolic demands of this specific routine to adjust the training plan accordingly to its specificity. Likewise, coaches should be aware that the neuromuscular structures might not recover as quickly as the cardiovascular and pulmonary systems, depending on crossfitters' training status and on the type of exercise performed.

Chapter 3

Effect of Fran CrossFit® workout on oxygen uptake kinetics, energetics, and postexercise muscle function in trained crossfitters

Manoel Rios,^{1,2} Klaus Magno Becker,^{1,2} Ana Sofia Monteiro,^{1,2} Pedro Fonseca,² David B. Pyne,³ Victor Machado Reis,^{4,5} Daniel Moreira-Gonçalves,^{6,7} and Ricardo J. Fernandes^{1,2}

¹Center of Research, Education, Innovation and Intervention in Sport, Faculty of Sport, University of Porto, Porto, Portugal

²Porto Biomechanics Laboratory, Faculty of Sport, University of Porto, Porto, Portugal

³Research Institute for Sport & Exercise, University of Canberra, Canberra, Australia

⁴Department of Sport Sciences, Exercise and Health, University of Trás-os-Montes e Alto Douro, Vila Real, Portugal

⁵Research Center in Sports Sciences, Health Sciences and Human Development, Vila Real, Portugal

⁶Research Center in Physical Activity, Health and Leisure, Faculty of Sport, University of Porto, Portugal

⁷Laboratory for Integrative and Translational Research in Population Health, Porto, Portugal

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Abstract

Fran is one of the most popular CrossFit® benchmark workouts and used to control crossfitters improvements. Detailed physiological characterization of Fran is needed for a more specific evaluation of crossfitters training performance improvements. The aim of the study was to analyze the oxygen uptake ($\dot{V}O_2$) kinetics, characterize the energy systems contributions, and the degree of postexercise fatigue of the unbroken Fran. Twenty trained crossfitters performed Fran at maximal exertion. $\dot{V}O_2$ and heart rate kinetics were assessed at baseline, during and post-Fran. The blood lactate and glucose concentrations, and muscular fatigue were measured at baseline and in the recovery period. Marked increase in $\dot{V}O_2$ kinetics was observed at the beginning of Fran, remaining elevated until the end [$\dot{V}O_{2peak}$: 49.2 (3.7) mL·kg⁻¹·min⁻¹, $\dot{V}O_2$ amplitude: 35.8 (5.2) mL·kg⁻¹·min⁻¹, time delay: 4.7 (2.5) s and time constant: 23.7 (11.1) s; mean (SD)]. Aerobic, anaerobic lactic and alactic pathways accounted for 62 (4), 26 (4) and 12 (2) % of energy contribution. Reduction in muscle function in jumping ability [jump height: 8 (6) %, peak force: 6 (4) % and maximum velocity: 4 (2) %] and plank prone test [46 (20) %] was observed in the recovery period. Fran unbroken workout is a high-intensity effort associated with an elevated metabolic response. This pattern of energy response highlights the primary contribution of aerobic energy metabolism, even during short and very intense CrossFit® workouts, and that recovery can take more than 24 h due to cumulative fatigue.

Key words: blood lactate; energy systems; training; recovery

Introduction

Oxygen uptake ($\dot{V}O_2$) kinetics is a useful non-invasive measure of the integrated capacity to transport and utilize O_2 for increasing the rate of muscular energy turnover (Howley et al., 1995; Jones & Burnley, 2009). The scientific community has grouped and described the $\dot{V}O_2$ kinetics during continuous exercise in three main exercise intensity domains: (i) low-moderate intensity where, after an initial $\dot{V}O_2$ rise, a $\dot{V}O_2$ steady state is achieved within 3 min of exercise; (ii) heavy intensity, in which a $\dot{V}O_2$ slow component appears superimposed to its fast initial fast component; and (iii) severe intensity, with $\dot{V}O_2$ elevated and continuing to rise over time after its fast component leading to maximal $\dot{V}O_2$ values (Whipp & Ward, 1990; Whipp & Wasserman, 1972; Zacca et al., 2019). A fourth intensity domain was proposed - the extreme exercise (Hill et al., 2002), referring to intensities in which $\dot{V}O_2$ rises very fast from the onset of exercise, but does not reach its maximum value due to the early development of fatigue (Hill et al., 2002).

Studies have reported that faster $\dot{V}O_2$ kinetics and reduced $\dot{V}O_2$ slow component amplitude are highly related with high levels of cardiorespiratory fitness and training status, as well as better tolerance to fatigue (Jones & Burnley, 2009; Koppo et al., 2004; Krustup et al., 2009). $\dot{V}O_2$ kinetics assessment has been conducted mainly in running, cycling, swimming and rowing (Jones et al., 2004; Pringle et al., 2002; Sousa, Figueiredo, et al., 2015), but its evaluation along CrossFit® workouts is non-existent. CrossFit® is a gym-based fitness movement centering on high-intensity interval training with over 5 million participants and over 14,000 locations worldwide (Dominski et al., 2021). CrossFit® routines require high power and technical proficiency, with short rest periods, leading to overload and substantial fatigue (Claudino et al., 2018; Rios et al., 2021). To assess fitness and changes in work capacity over time, CrossFit® has introduced standardized exercises called benchmark workouts that differ in their specific exercises, structure, physical demands and scoring mechanism, including the total number of repetitions within a given time frame or the time to achieve a certain number of executions (Claudino et al., 2018; Leitão et al., 2021). Part of CrossFit® research is dedicated to finding predictive variables for performance in benchmark workouts using traditional laboratory

tests (Butcher et al., 2015; Dexheimer et al., 2019; Leitão et al., 2021; Zeitz et al., 2020). However, given the specificity of these workouts, the use of traditional testing protocols is limited as the physiological demands differ from those in a real-world training context (Rios et al., 2022; Rios et al., 2023).

From the several CrossFit® workouts that are available, Fran is one of the most popular and used to monitor crossfitters improvements (Leitão et al., 2021; Rios et al., 2022). Fran is a time-scored routine, consisting of three rounds of 21-21, 15-15 and 9-9 front squat to press overhead (using 43 and 30 kg barbells for males and females, respectively) plus pull-ups repetitions (Rios et al., 2022). Fran can elicit high values of blood lactate [La^-] (Leitão et al., 2021; Rios et al., 2023; Tibana et al., 2018) and glucose [Glu] (Rios et al., 2023) concentrations, heart rate (HR) (Leitão et al., 2021; Rios et al., 2023; Tibana et al., 2018) and $\dot{\text{V}}\text{O}_2\text{peak}$ (Rios et al., 2023), as well as a high rating of perceived exertion (RPE) (Leitão et al., 2021; Rios et al., 2023; Tibana et al., 2018) during the three rounds. In addition, a predominance of the anaerobic component (~59%) was observed for the completion of intermittent Fran (Rios et al., 2023). Post-Fran, a reduction in muscle functional capacity was observed. However, the specific energy contributions and corresponding recovery of muscle functionality may have been influenced by the 30-s intervals between the three rounds of the Fran (Rios et al., 2023). Additional information on the energetic and physical demands of this workout would be useful for crossfitters, trainers, and researchers interested in these issues. The aim of the study was to analyze the $\dot{\text{V}}\text{O}_2$ kinetics and the contributing proportion of each energy systems, to Fran conducted at maximal exertion and without breaks. We also assessed the degree of post-Fran fatigue and analyzed the recovery time course. We hypothesize that the specific cardiorespiratory demands of Fran align with the severe intensity domain classification.

Methods

Participants

Twenty trained crossfitters (n= 14 males and 6 females) were recruited with the following characteristics: age 29.6 (6.0) and 26.2 (3.5) years, height 174.1 (5.9) and 164.8 (3.8) cm, body mass 78.4 (6.9) and 66.2 (3.5) kg, body mass index

25.6 (1.7) and 23.8 (1.1) kg/m² and CrossFit® training experience 5.9 (1.1) and 6.1 (1.9) years (respectively), were recruited to participate. Subjects were engaged in a CrossFit® training frequency > five times per week for at least three years before the start of the study and recruited via personal contact based on the following eligibility criteria: (i) ability to perform Fran without pauses between rounds; (ii) not presenting with any physical impairments; (iii) between 18-40 years of age; (iv) were not using performance enhancing drugs and; (v) free to exercise according to Physical Activity Readiness Questionnaire (PARQ). All the procedures were approved by the local Ethics Committee (CEFADE 21 2019), with participants reading and signing an informed consent form in accordance with the Declaration of Helsinki.

Experimental design

We employed a single group of experienced crossfitters to evaluate the physiological demands of Fran in a prospective gym-based study. After being familiarized with the procedures and performing a 15 min individualized low-intensity warm-up (joint mobility plus Fran's specific exercises), participants performed Fran at maximal exertion. A suite of physiological and energetic variables was measured at baseline, during and after Fran. Crossfitters also performed three countermovement jumps (30-s intervals in-between) and a prone plank exercise to assess muscle function responses at baseline and 5 min, 30 min and 24 h post-Fran.

Methodology

Height and body mass were obtained using a digital scale with a built-in stadiometer (SECA, model 220, Germany), with body mass index determined as the ratio between body mass and squared height. Pulmonary gas exchange was measured breath-by-breath at rest, during and post-Fran using a K4b² telemetric portable gas analyzer (Cosmed, Rome, Italy) attached to the participant's back (near their body center of mass to limit interference with their movements; Figure 1). HR was measured continuously by a Polar T34 Heart Rate Transmitter (Polar, Kempele, Finland) that telemetrically emitted the data to the K4b² portable unit.

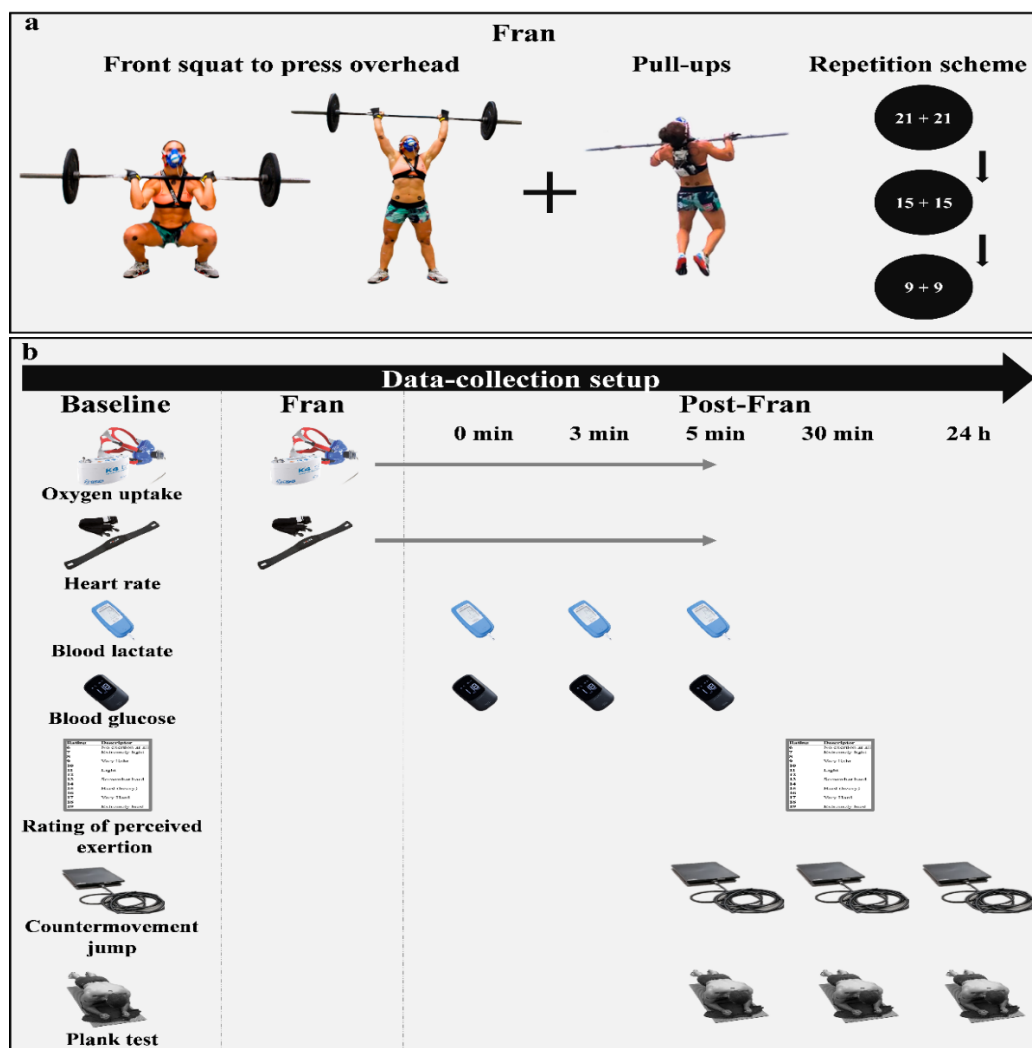


Figure 1. Fran routine, with crossfitters wearing a portable gas analyzer (a) and data-collection time-course (b).

Capillary blood samples (5 μ L) were collected from the earlobe at baseline and at 1st, 3rd and 5th min post-Fran for [La⁻] and [Glu] assessment was reached using a Lactate Pro 2 (Arkay, Inc, Kyoto, Japan) and Accu-Chek Aviva (Mannheim, Germany) analyzer. The 6-20 Borg scale was used to assess RPE at baseline and 30 min post-Fran (Figure 1). Information about the RPE was explained to the participants individually according to established recommendations (Noble & Robertson, 1996). Fran trials were performed in the same facility and under similar environmental conditions (22°C ambient temperature, 60% humidity and between 8-12 noon). All crossfitters were instructed to maintain the same individual nutritional habits and to avoid intake of alcohol, and caffeine hard physical activity for 48 h prior and 24 h after the test.

The $\dot{V}O_{2\text{peak}}$ and mean values of all ventilatory parameters were assessed using data from the last 30-s of Fran (Howley et al., 1995), with breath-by-breath data edited to exclude errant breaths from coughing or signal interruptions (Sousa, Figueiredo, et al., 2015; Zacca et al., 2019). Only the values between mean ± 3 SD were included for analysis, and posteriorly smoothed using a moving and time average of three breaths and 10-s (Sousa, Figueiredo, et al., 2015). The $\dot{V}O_2$ kinetics parameters were estimated, including the precision of estimation, by bootstrapping with 1000 samples (Curran-Everett, 2009), with the cardiodynamic phase not considered in the analysis (Sousa, Figueiredo, et al., 2015). The on-transient $\dot{V}O_2$ of Fran and the post-exercise $\dot{V}O_2$ (EPOC) were estimated with mono-exponential and bi-exponential models using the VO2FITTING software (Zacca et al., 2019):

$$\dot{V}O_2(t) = A_0 + H(t - T_{D_p}) A_p (1 - e^{-(t - T_{D_p})/\tau_p})$$

$$\dot{V}O_2(t) = A_0 - H(t - T_{D_p}) A_p (1 - e^{-(t - T_{D_p})/\tau_p}) - H(t - T_{D_{sc}}) A_{sc} (1 - e^{-(t - T_{D_{sc}})/\tau_{sc}})$$

where $\dot{V}O_2(t)$ represents the relative $\dot{V}O_2$ at the time t , A_0 is the $\dot{V}O_2$ at rest, H represents the Heaviside step function (Ma et al., 2010), A_p and A_{sc} , τ_p and τ_{sc} , T_{D_p} and T_{sc} are the amplitude, time constant and time delay of the $\dot{V}O_2$ fast and slow components (Barstow et al., 1993; Zacca et al., 2019). The accumulated $\dot{V}O_2$ was obtained from the relationship between time integral of the net $\dot{V}O_2$ vs the time exercise duration (Rios et al., 2023; Tabata et al., 1997).

The aerobic energy contribution was calculated using the time integral of the net $\dot{V}O_2$ vs time relationship, and the anaerobic contributions using the following equations: $\text{alactic} = \text{PCr} \cdot (1 - e^{-t/\tau}) \cdot M$, where PCr is the phosphocreatine concentration at rest, t is Fran time, τ is the time constant of the PCr splitting at exercise onset (23.4 s) and M (kg) is the body mass and $\text{lactic} = [\text{La}^-]_{\text{net}} \cdot \beta \cdot M$, where $[\text{La}^-]_{\text{net}}$ is the net accumulation of lactate after Fran, β is the constant for O_2 equivalent of $[\text{La}^-]_{\text{net}}$ ($3 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{mM}^{-1}$) and M (kg) is the body mass (Rios et al., 2022; Sousa, Figueiredo, et al., 2015; Zamparo et al., 2011). Energy systems contributions were expressed using an energy equivalent of $20.9 \text{ kJ} \cdot \text{L}^{-1}$ (Rios et al., 2022; Sousa, Figueiredo, et al., 2015; Zamparo et al., 2011) and the total energy expenditure was calculated as the sum of aerobic and

anaerobic (alactic plus lactic) energy pathways (Di Prampero, 1986; Rios et al., 2023; Sousa, Figueiredo, et al., 2015). Metabolic power was estimated as the ratio between energy expenditure and exercise time, (Rios et al., 2023; Sousa, Figueiredo, et al., 2015; Zamparo et al., 2011) and caloric expenditure estimated by multiplying absolute $\dot{V}O_2$ by 5.05 kcal·L⁻¹ assuming an energy equivalent of 4.184 kJ·L⁻¹ (Ratamess et al., 2015; Reis et al., 2019).

Three countermovement jumps (30-s intervals in-between) were performed on a OR6-WP portable force platform (AMTI, Watertown, USA), with the best jump used to calculate duration, height, force and velocity (Rios et al., 2023). These variables were computed from the force-velocity, -time and -acceleration curves using a custom-made MATLAB R2020b routine (MATLAB, MathWorks, Natick, MA, USA). In the prone plank test, the time (using a chronometer Seiko, Tokyo, Japan) that participants maintained the position with the body weight supported by the toes and forearms was measured. The test was finished when the individual was not able to hold the back straight and the hips were lowered (Timón et al., 2019).

Statistical analysis

Based on a priori power analysis (β) of 0.80, a moderate effect size (0.25) and an overall level of significance of 0.05, a sample size of 20 participants proved adequate for conducting the study (G*Power 3.1.9.7, Heinrich-Heine-Universität Düsseldorf, Germany). Computations were completed using GraphPad Prism 6 and mean $\pm$ SD and/or two-sided 95% confidence interval are reported for all variables. The Shapiro-Wilk test was used to assess data normality, and repeated-measures analysis of variance (with a Bonferroni post-hoc test) was employed to analyze differences between cardiorespiratory, energetic and fatigue-related variables at different time points of Fran. Repeated measures t-test was applied to compare perceived exertion and metabolic variables before and after Fran. The effect size was calculated with Cohen's d and interpreted as follows: trivial if $|d| < 0.2$, medium if $0.2 > |d| < 0.5$, and large if $|d| \geq 0.5$. Statistical significance level set at 5%.

Results

The overall Fran duration was 198 [184-211] s (respectively mean [95% CI]), with an exercise frequency of 0.5 [0.4-0.5] repetition/s and a $\dot{V}O_2$ primary component amplitude of 35.8 [33.2-38.2] $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$, time delay 4.7 [3.5-5.9] s and time constant value of 23.7 [18.3-29.0] s. An individual example of the $\dot{V}O_2$ kinetics, deficit, accumulated and excess postexercise $\dot{V}O_2$ responses is shown in Figure 2. The accumulated $\dot{V}O_2$ during Fran and the EPOC were 7.7 [6.9-8.37] $\text{L}\cdot\text{min}^{-1}$ and 4.4 [3.9-4.8] $\text{L}\cdot\text{min}^{-1}$.

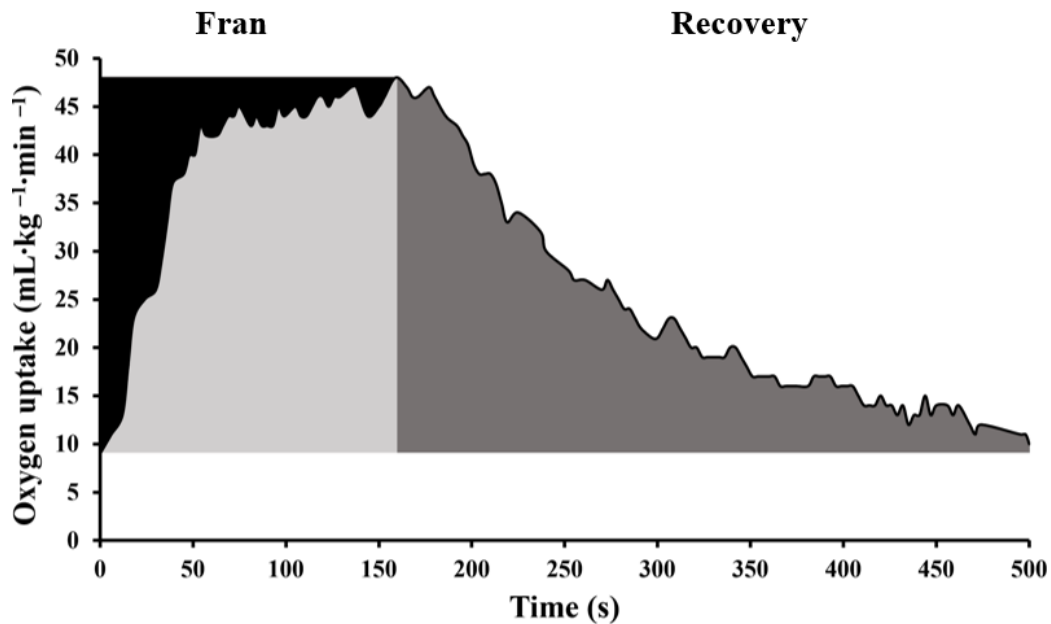


Figure 2. Example of the $\dot{V}O_2$ kinetics during and post-Fran. The respective accumulated O_2 deficit, accumulated $\dot{V}O_2$ and excess postexercise $\dot{V}O_2$ are illustrated using black, light and dark grey (respectively).

Table 1 details the values of measured physiological variables at baseline and during Fran, with the $\dot{V}O_{2\text{peak}}$, minute ventilation, respiratory frequency, tidal volume, respiratory exchange ratio, HR mean (180 [178-171] $\text{b}\cdot\text{min}^{-1}$, $p = 0.001$, $d = 15.7$), HR peak, $[La^-]$, $[Glu]$ and RPE values higher during exercise comparing to baseline. The minute ventilation (73.8 [65.0-83.0] $\text{L}\cdot\text{min}^{-1}$, $p = 0.001$, $d = 4.0$), respiratory frequency (34.9 [31.7-37.8] $\text{b}\cdot\text{min}^{-1}$, $p = 0.001$, $d = 3.6$), tidal volume (2.2 [2.0-2.5] L, $p = 0.001$, $d = 3.7$) and HR (134 [128-140] $\text{b}\cdot\text{min}^{-1}$, $p = 0.001$, $d = 5.3$) values remained elevated at the 5th of recovery compared to baseline, with higher respiratory exchange ratio values (1.5 [1.4-

1.5]) than at both baseline ($p = 0.001$, $d = 4.4$) and exercise ($p = 0.001$, $d = 3.0$) conditions.

Table 1. Baseline and Fran physiological demands.

Variable	Baseline	Fran	p	d
Peak oxygen uptake, mL·kg ⁻¹ ·min ⁻¹	6.6 (1.1) [6.0-7.1]	49.2 (3.7) [47.7-50.9] *	< .001	15.6
Minute ventilation, L·min ⁻¹	16.7 (2.9) [15.3-18.0]	132.7 (20.4) [123.1-142.2] *	< .001	7.9
Respiratory frequency, b·min ⁻¹	17.0 (2.4) [15.9-18.1]	57.5 (10.1) [52.7-62.2] *	< .001	5.5
Tidal volume, L	0.8 (0.2) [0.6-0.9]	2.4 (0.4) [2.1-2.5] *	< .001	0.5
Respiratory exchange ratio	0.8 (0.2) [0.7-0.8]	1.2 (0.1) [1.1-1.2] *	< .001	2.5
Peak heart rate, b·min ⁻¹	84 (8) [80-88]	185 (6) [182-188] *	< .001	14.9
Peak blood lactate, mmol·L ⁻¹	1.5 (0.4) [1.2-1.6]	16.1 (2.9) [14.3-17.4] *	< .001	7.0
Peak blood glucose, mg·dL ⁻¹	95.7 (6.8) [93.5-102.4]	143.4 (30.4) [130.0-157.7] *	< .001	2.1
Rating of perceived exertion, 6-20 scale	6 (0) [6-6]	17 (1) [16-17] *	< .001	2.2

The respective Mean $\pm$ SD, 95% confidence intervals, probabilities (p) and significant effect sizes (d) are also displayed. * Differences from baseline.

The absolute and relative aerobic and anaerobic lactic systems contribution throughout Fran were higher than the anaerobic alactic system (Figure 3). Total energy expenditure and metabolic power values during Fran were 260 [240-280] kJ and 1.3 [1.2-1.4] Kw. The caloric expenditure was higher during Fran when compared to the recovery period (162 [148-177] vs 92 [82-101] kJ, $p = 0.001$, $d = 2.7$).

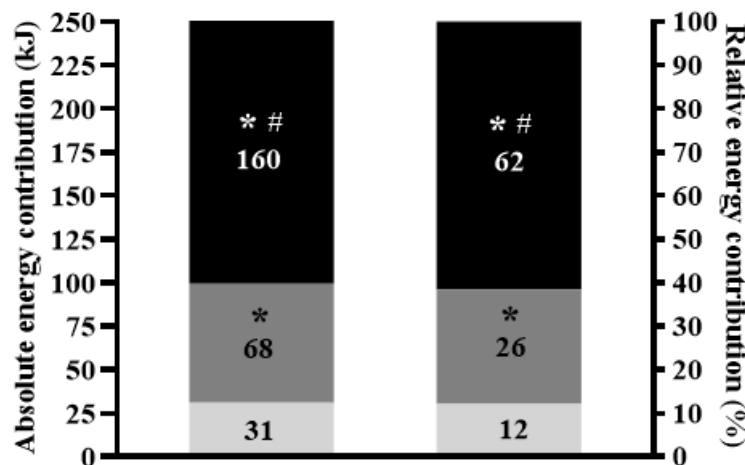


Figure 3. Fran (absolute and relative) aerobic, anaerobic lactic and anaerobic alactic (black, dark grey and light grey) energy contributions. * Differences from anaerobic alactic ($p < 0.001$). # Differences from anaerobic lactic ($p < 0.001$).

Figure 4 displays the post-Fran muscular function values. When compared to baseline the following changes were observed:

- (i) *jump height* decreased 5 min (34.0 [32.2-35.9] vs 31.4 [29.5-33.3] s, respectively mean [95%CI]; $p = 0.001$, $d = 0.6$), 30 min (31.7 [29.4-33.9] s; $p = 0.001$, $d = 0.5$) and 24 h (32.7 [30.8-34.6] s; $p = 0.001$, $d = 0.3$) post-Fran, while increased 24 h of the recovery period compared to 5 min ($p = 0.008$, $d = 0.3$) and 30 min ($p = 0.015$, $d = 0.2$) post-Fran;
- (ii) *jump duration* decreased at 5 min (1.0 [0.9-1.1] vs 0.8 [0.7-0.8] s; $p = 0.169$, $d = 1.2$) and 30 min (0.8 [0.7-0.8] s; $p = 0.046$, $d = 1.2$) of the recovery period. An increase was observed at post 30 min ($p = 0.045$, $d = 0.0$) and 24 h (0.8 [0.8-0.9] s; $p = 0.016$, $d = 0.0$) compared to 5 min post-Fran;
- (iii) *concentric jump duration* decreased 5 min (0.27 [0.25-0.29] vs 0.25 [0.23-0.26] s; $p = 0.001$, $d = 0.2$) and 30 min (0.26 [0.24-0.27] s; $p = 0.015$, $d = 0.1$) post-Fran, with an increase at 24 h of the recovery period (0.26 [0.25-0.28] s; $p = 0.084$, $d = 0.1$) compared to 5 min post-Fran;
- (iv) *eccentric jump duration* (0.70 [0.60-0.80] vs 0.60 [0.55-0.65] s; $p = 0.047$, $d = 4.4$), peak force (24.7 [26.6-25.8] vs 23.9 [23.0-24.8] N/kg; $p = 0.016$, $d = 0.5$) and eccentric peak force (22.6 [21.1-24.0] vs 21.3 [19.9-22.7] N/kg; $p = 0.001$, $d = 0.4$) all declined during the 24 h of the recovery period;
- (v) *maximum velocity* dropped at 5 min (2.7 [2.6-2.7] vs 2.5 [2.5-2.6] m/s; $p = 0.001$, $d = 0.6$) and 30 min (2.6 [2.5-2.6] m/s; $p = 0.001$, $d = 0.5$) of the recovery period, presenting higher values at 24 h compared to post-5 min (2.6 [2.6-2.7] m/s; $p = 0.026$, $d = 0.4$) and 30 min ($p = 0.012$, $d = 0.3$) post-Fran;
- (vi) *plank prone* performance decreased over 24 h (226.2 [197.1-256.4] vs 199.9 [171.1-228.6] s; $p = 0.019$, $d = 0.4$) post-Fran but higher values were observed at 30 min (156.3 [134.4-178.2] s; $p = 0.001$, $d = 0.6$) and 24 h compared to 5 min (126.2 [100.4-152.0] s; $p = 0.001$, d

= 1.2) post-Fran, and an increase was observed at 24 h ($p = 0.001$, $d = 0.9$) vs 30 min post-Fran.

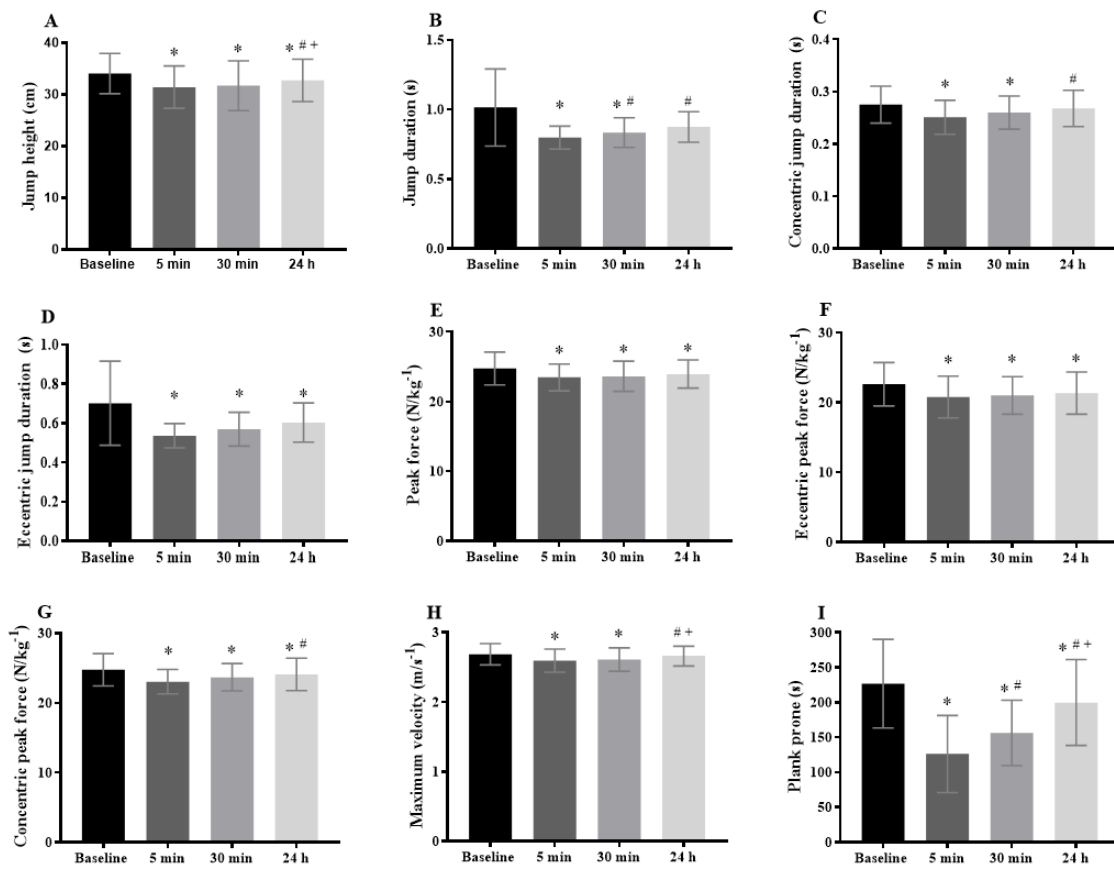


Figure 4. Muscular fatigue variables mean $\pm$ SD values obtained post-Fran. *Different from baseline ($p < 0.05$). # Different from 5 min post-Fran ($p < 0.05$). + Different from 30 min post-Fran ($p < 0.05$).

Discussion

Detailed physiological and metabolic assessment of CrossFit® workouts informs the development and evaluation process by trainers and researchers. We have demonstrated that Fran resulted in greater primary amplitude of the $\dot{V}O_2$ kinetics, in accordance with previous results in other severe intensity exercise modalities (Carter et al., 2002; Sousa, Figueiredo, et al., 2015; Sousa, Rodríguez, et al., 2015). There was an increase in the anaerobic lactic system contribution during Fran. However, the aerobic energetic system contribution corresponded to ~62% of the total energy demand of Fran. Our data also shows that a single Fran results in significant fatigue, that is still present 24 h after the

challenge. Collectively these outcomes indicate the high energetic demands of Fran and confirms its utility and potency in the prescription of CrossFit® training sessions.

An instantaneous and sudden increase in $\dot{V}O_2$ from the beginning of Fran was observed that continued to rise along the exercise. Indeed, we observed $\dot{V}O_{2peak}$ of 49.2 (3.7) mL·kg⁻¹·min⁻¹ and accumulated $\dot{V}O_2$ of 7.7 (1.5) L·min⁻¹. This is higher than when Fran is performed in an intermittent fashion ($\dot{V}O_{2peak}$ of 46.1 (4.1) mL·kg⁻¹·min⁻¹ and accumulated $\dot{V}O_2$ of 6.8 (2.2) L·min⁻¹) (Rios et al., 2023). In addition, previous studies conducting a standard (Butcher et al., 2015; Dexheimer et al., 2019) maximal and/or peak $\dot{V}O_2$ assessments using treadmill running in experienced crossfitters reported values ranging from 48.6 to 54.7 mL·kg⁻¹·min⁻¹, which is near the range of values reported here for unbroken Fran. Thus, with such $\dot{V}O_2$ mean amplitude, unbroken Fran seems to be aligned with the severe exercise intensity domain (Kramer et al., 2018; Sousa, Figueiredo, et al., 2015). Moreover, we have report larger time constant values than those described with cycling, swimming and rowing athletes performing exercise the severe intensity domain (Pringle et al., 2003; Sousa, Figueiredo, et al., 2015). The difference observed in this study can be explained by the fact that Fran was performed with maximum effort (without breaks) (Rios et al., 2023) from the beginning, as well as by the muscle mass and type involved in each exercise modality (Sousa, Figueiredo, et al., 2015). These outcomes are evidence that appropriate O₂ supply and utilization should not be neglected even in short duration CrossFit® efforts.

The faster $\dot{V}O_2$ kinetics at the beginning of Fran reduced the magnitude of the O₂ deficit. This faster adjustment of the aerobic pathway is associated with a shorter time lag in the imbalance between $\dot{V}O_2$ demand and supply, implies an augmented oxidative contribution to energy transfer (Burnley & Jones, 2007; Gastin, 2001). As expected, minute ventilation, tidal volume, respiratory frequency and respiratory exchange ratio increased along the studied Fran, consistent with other types of exercises (Ribeiro et al., 2015; Sousa, Figueiredo, et al., 2015). During exercise, minute ventilation increases due to the increase of both tidal volume and respiratory frequency, and can exceed more than 20 times the resting levels (Guenette & Sheel, 2007). With the increase of these

ventilatory variables, the respiratory exchange ratio increased in the exercise condition, indicating an imbalance in the metabolic process of CO₂ release and O₂ uptake during Fran (Howley et al., 1995). The high values of mean and peak HR, RPE, [La⁻] and [Glu] are in line with other studies that evaluated Fran (Leitão et al., 2021; Rios et al., 2023; Tibana et al., 2018). This cardiovascular and metabolic stress can be attributed to the high intensity, given that Fran aims to complete the repetition scheme in the shortest possible time (Tibana et al., 2018).

The energy contributions (kJ and %) values corroborate our hypothesis, evidencing a higher contribution from the aerobic system to adenosine triphosphate resynthesis along Fran (Gastin, 2001). We observed a substantial contribution of the anaerobic lactic system and a smaller involvement of the alactic anaerobic system. While the increase in lactic anaerobic contribution must be attributed to the peak of [La⁻] after exercise (Sousa, Figueiredo, et al., 2015; Zamparo et al., 2011), the lower alactic anaerobic contribution can simply be attributed to the duration total of Fran (Gastin, 2001; Zamparo et al., 2011). Our results indicate that the aerobic contribution is higher during Fran executed at maximal effort (62%) compared to intermittent Fran (41%) (Rios et al., 2023), while the predominance of anaerobic energy (alactic plus lactic) is higher when Fran is performed with intervals (59%) (Rios et al., 2023). It is possible that the 30-s intervals between the rounds in the intermittent Fran influenced the restoration of O₂ stores and phosphocreatine resynthesis, increasing the anaerobic contribution (Gastin, 2001; Tabata et al., 1997). A high total energy expenditure and metabolic power was observed during workout, indicative of an increasing energy demand for completion of high-intensity actions (Da Silva et al., 2010; Ratamess et al., 2015). The increase in caloric expenditure during the recovery can be attributed to the volume and intensity of the workout, reflecting the increase in EPOC during the return to homeostasis (Da Silva et al., 2010; Ratamess et al., 2015).

During the recovery period, the cardiopulmonary variables remained elevated when compared to baseline. It is important to note that the respiratory exchange ratio increased compared with Fran. This increase could be due to the contribution of nonmetabolic CO₂ production from bicarbonate buffering of

hydrogen ions produced during Fran (Poole et al., 2021). The excess $\dot{V}O_2$, HR plus concentrations $[La^-]$ and $[Glu]$ values post-Fran likely influenced this stress (Gaesser & Brooks, 1984; Reis et al., 2019). Cardiorespiratory function remains high so that sufficient O_2 and substrates are provided to the tissues, while waste products are removed (Gaesser & Brooks, 1984; Reis et al., 2019). The jumping ability and performance in plank prone were impaired 24 h post-Fran, which aligns with a recent study that evaluated muscle function after Fran (Rios et al., 2023). The higher metabolic stress (e.g. high values of $[La^-]$ and $[Glu]$) induced in a CrossFit® training reduce muscle function (Rios et al., 2023). It is well known that maximal muscular work can potentially impair type II muscle fiber, correlated with increased serum creatine kinase concentration and the time required in the recovery post-Fran (Halsen, 2014). The reduction in performance prone plank can be attributed to Fran exercises, which require stability and activation of the central muscles of the body (Timón et al., 2019).

Some limitations of the current study should be highlighted. First, it is important to note that in this study, there was no a priori test conducted to determine the maximal $\dot{V}O_2$ of the crossfitters. Consequently, it was not possible to precisely determine the intensity domain in which Fran was performed. Therefore, our results should be interpreted with caution because the cardiorespiratory function results observed during Fran may not be aligned with the severe intensity domain. It is worth noting that some studies have demonstrated a low correlation between predictors of Fran performance and maximal aerobic capacity as determined by laboratory protocols (Butcher et al., 2015; Dexheimer et al., 2019; Leitão et al., 2021; Zeitz et al., 2020). Furthermore, advocating an a priori standardized testing protocol to determine maximal $\dot{V}O_2$ and comparing it to Fran performance that includes specific strength training elements may be neglecting the principle of modality specificity in sports training (Sandbakk et al., 2021). Secondly, we recognize that exercise performance from females could be influenced by the menstrual cycle phases, but since we did not collect this information, it was not possible to make any consideration about this issue. Finally, performance and recovery are known to be influenced by nutritional status, sleep quality and hydration, which we did not assessed; however, we asked for all crossfitters to maintain the same individual nutritional habits and to

avoid behaviors known to negatively impact performance and recovery. Future studies of this nature should consider conducting a priori tests (following the principle of specificity) to determine maximal $\dot{V}O_2$, enabling the classification of the intensity domain for unbroken Fran performance. Longitudinal studies analysing cardiorespiratory function, fatigue status and recovery in response to multiple days of CrossFit® training using similar methods may be important for a better understanding of performance changes, fatigue, and recovery markers in subjects of both sexes and with different CrossFit® experience background.

Conclusion

During a high-intensity Fran, an instantaneous and sudden increase of the $\dot{V}O_2$ occurred at the beginning of the exercise, and continued to rise until the end of the bout. This pattern of energy response highlights the substantial contribution of the aerobic energy pathway even in short and very intense CrossFit® workouts. Nevertheless, considering that ~38 % of total energy was obtained anaerobically, both energy systems should be strengthened to improve Fran performance. In addition, a reduction in muscle function was observed over the 24 h follow-up period, so CrossFit® training should be monitored and adjusted according to energy demands, optimizing recovery and avoiding/minimizing injuries.

Practical applications

Fran is one of the most popular CrossFit® benchmarks and used to track crossfitters improvements in fitness and performance. The findings indicate that performing unbroken Fran elicits a substantial cardiorespiratory response, consistent with recommendations for improving cardiovascular fitness. It is important to note the observed increase in metabolic responses and perceived exertion, as well as the decrease in performance on the countermovement jump and plank tests post-Fran. These outcomes highlight the need for adequate recovery between successive Fran sessions. In addition, unbroken Fran can be used strategically to stimulate adaptations in the aerobic pathway, whereas intermittent Fran is effective in promoting adaptations in the anaerobic pathway.

Chapter 3

Pros and cons of two methods of anaerobic alactic energy assessment in a high-intensity CrossFit® workout

Manoel Rios¹, Victor Machado Reis^{2,3}, Susana Soares¹, Daniel Moreira-Gonçalves^{4,5} and Ricardo J. Fernandes¹

¹Center of Research, Education, Innovation and Intervention in Sport, Faculty of Sport and Porto Biomechanics Laboratory, Faculty of Sport, University of Porto, 4200-450 Porto, Portugal

²Department of Sport Sciences, Exercise and Health, University of Trás-os-Montes e Alto Douro, 5001-801 Vila Real, Portugal

³Research Center in Sports Sciences, Health Sciences and Human Development, 5001-801 Vila Real, Portugal

⁴Research Center in Physical Activity, Health and Leisure, Faculty of Sport, University of Porto, 4200-450 Porto, Portugal

⁵Laboratory for Integrative and Translational Research in Population Health, 4050-091 Porto, Portugal

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Abstract

The current study aimed to evidence the strengths and weaknesses of two indirect methods for assessing the anaerobic alactic contribution to a specific CrossFit® workout. Thirty experienced crossfitters performed the Fran workout at maximal intensity, and ventilatory data were collected during the recovery period using a telemetric portable gas analyser to assess the oxygen uptake ($\dot{V}O_2$) of the off-kinetics fast component ($Ana_{recovery}$). The kinetics of maximal phosphocreatine splitting (Ana_{PCr}) were determined based on the literature. No differences between the two methods were observed (31.4 ± 4.0 vs. 30.4 ± 4.1 kJ for $Ana_{recovery}$ and Ana_{PCr} , respectively). Despite the existence of some caveats (e.g., errors derived from a delay at the onset of $\dot{V}O_2$ recovery and the assumption of given values in the concentration of phosphocreatine per kilogram of wet muscle, respectively) in both methods, the data indicate that they yield similar results and allow for estimations of alactic energy contribution from a short-duration and high intensity CrossFit® routine. The current data contributes to CrossFit® workout evaluations and training strategies, helping researchers to evaluate crossfitters more accurately. The advantage of the two methods used in the current study is that they are non-invasive, which differs greatly from muscle biopsies.

Key words: anaerobic alactic contribution; phosphocreatine; oxygen uptake

Introduction

Sports bioenergetics have been studied since the 1920s, with a focus on locomotion and its contribution to athletic performance (Zamparo et al., 2011). The capability to produce mechanical work during physical exertion is ultimately determined by the muscle cells' ability to provide energy by means of two distinct but integrated metabolic processes: the anaerobic and the aerobic pathways (Gastin, 2001). Aerobic energy release is readily quantified, since there is a direct relationship between the oxygen uptake ($\dot{V}O_2$) measured at the mouth and the whole-body aerobic production of adenosine triphosphate (Gastin, 2001; Beneke et al., 2002). Of the two components of anaerobic energy contribution, the lactic system is more often investigated, because it can be estimated based on the net increase in blood lactate concentration at the end of the exercise, and assumes a given energy equivalent for lactate (Reis et al., 2011; Zamparo et al., 2011).

The anaerobic alactic contribution has been estimated by assuming that phosphocreatine (PCr) concentration in active muscles decreases by a known amount and with a given kinetics (Ana_{PCr}) in the transition from rest to exhaustion (Gastin, 2001; Sousa, Figueiredo, et al., 2015). Another anaerobic alactic contribution estimation is calculated based on the post-exercise $\dot{V}O_2$ fast component ($Ana_{recovery}$), since the greatest part of the O_2 debt has been interpreted as the energy necessary to rebuild the high energy phosphate compounds which were split at the exercise onset (Beneke et al., 2002; Di Prampero & Margaria, 1968). These methods have been applied before in different exercise modes (Davis et al., 2014; Sousa et al., 2013; Sousa, Rodrigues, et al., 2015), and are based on questionable assumptions, such as the PCr concentration rest value and $\dot{V}O_2$ on response time constant at the muscular level. Moreover, the assumption that the post-exercise $\dot{V}O_2$ fast component is independent of blood lactic acid removal has also been questioned (Gastin, 2001).

CrossFit® workouts comprise functional movements performed at high intensity, and are typically composed of gymnastic-type exercises, metabolic-related conditioning and weightlifting (Butcher et al., 2015; Rios et al., 2021). Fran is

one of the most popular CrossFit® benchmarks, a time-scored workout consisting of three rounds of 21, 15 and 9 front squat to press overheads (using a 43 and 30 kg barbell for males and females, subjects dropped the hips below the knees and finished the exercise with the knees, hips and elbows in full extension) plus pull-ups (the chin needed to pass the bar) repetitions (Butcher et al., 2015; Leitão et al., 2021). This workout is used to evaluate crossfitters' performance improvements, and is directly related to anaerobic thresholds obtained on a cycle ergometer (Butcher et al., 2015). Given the necessity of a more specific method to assess CrossFit® performance, the use of both aforementioned methods still warrants further research. The current study aimed to evidence the strengths and weaknesses of two methods for assessing the anaerobic alactic contribution of a specific CrossFit® workout: (i) using the $\dot{V}O_2$ off kinetics fast component, and (ii) estimating the maximal phosphocreatine splitting in the contracting muscle.

Materials and methods

Subjects and data collection

Thirty participants (21 males and 9 females) with $\geq$ five years of previous CrossFit® training experience volunteered to participate in the current study (28.3 ± 6.2 and 25.2 ± 3.7 years old, 174.5 ± 5.8 and 161.7 ± 4.8 cm of height and 78.2 ± 7.6 and 64.1 ± 3.4 kg of body mass, respectively). All crossfitters were instructed to maintain the same individual nutritional habits and to avoid intake of alcohol and caffeine (as well as hard physical activity) 48 h prior to the test. All volunteers were informed about the experimental procedures, associated risks and benefits of participation. The experimental procedures were approved by the Ethics Committee of the Faculty of Sport at the University of Porto (CEFAD212019), and followed the Declaration of Helsinki and the guidelines of the World Medical Association for research on humans.

The experiments were conducted at a full equipped laboratory facility with $\sim 22^\circ\text{C}$ room temperature and 55% relative humidity. After being familiarized with the procedures and accomplishing a 10 min individualized low intensity warm-up (joint mobility plus Fran's specific exercises), participants performed the Fran workout at maximal effort (Butcher et al., 2015). Performance was

measured using a stopwatch (Seiko, Yokohama, Japan) and post-workout respiratory gas exchange was measured breath-by-breath using a portable gas analyser for five minutes (Cosmed K4b2, Cosmed, Rome, Italy) (Monteiro et al., 2020). To omit errant breaths (e.g., swallowing and coughing) and to reduce the eventual noise from this acquisition, data were edited according to previously described procedures (Monteiro et al., 2020).

Data processing

The anaerobic alactic contribution was determined using the $\dot{V}O_2$ off-kinetics fast component in the Fran workout—Ana_{recovery} (Beneke et al., 2002; Sousa et al., 2013). To determine the fast and slow component kinetics, mono- and bi-exponential models were computed (Equations (1) and (2)) using VO2FITTING software (Zacca et al., 2019) for data analysis and treatment, as well as for editing and modelling participants' responses:

$$\dot{V}O_2(t) = A_0 + H(t - T_{D_p}) A_p (1 - e^{-(t - T_{D_p})/\tau_p}) \quad (1)$$

$$\dot{V}O_2(t) = A_0 - H(t - T_{D_p}) A_p (1 - e^{-(t - T_{D_p})/\tau_p}) - H(t - T_{D_{sc}}) A_{sc} (1 - e^{-(t - T_{D_{sc}})/\tau_{sc}}) \quad (2)$$

where $\dot{V}O_2(t)$ represents the relative $\dot{V}O_2$ at the time t , A_0 is the $\dot{V}O_2$ at rest, H represents the Heaviside step function, A_p and A_{sc} , τ_p and τ_{sc} , T_{D_p} and $T_{D_{sc}}$ are the amplitude, time constant and time delay of the off- $\dot{V}O_2$ fast and slow components, respectively (Zacca et al., 2019). Ana_{recovery} was determined as the $\dot{V}O_2$ time integral derived from the off-fast component, assuming an energy equivalent of 20.9 kJ·L⁻¹ (Zamparo et al., 2011; Sousa, Figueiredo, et al., 2015). Peak oxygen uptake ($\dot{V}O_{2peak}$) was obtained by backward extrapolation at zero recovery time using values from the first 20 s of recovery (Figure 1) (Monteiro et al., 2020).

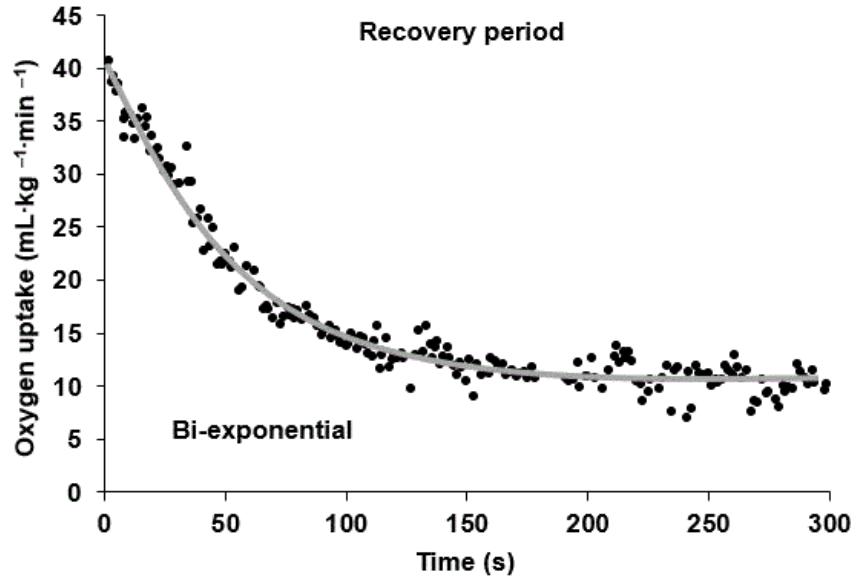


Figure 1. Individual oxygen uptake curve during the recovery period after the Fran workout (bi-exponential model fit).

The anaerobic alactic contribution was also estimated using the maximal PCr splitting in the contracting muscle, by assuming an energy equivalent of 0.468 kJ·mM⁻¹ and a phosphate/oxygen ratio of 6.25 (Equation (3)) (Zamparo et al., 2011; Sousa, Figueiredo, et al., 2015):

$$\text{Ana}_{\text{PCr}} = \text{PCr} \cdot (1 - e^{-t/\tau}) \cdot M \quad (3)$$

where PCr is the phosphocreatine concentration at rest, assumed to be 18.55 mmol·kg⁻¹ in maximally active muscle mass (Capelli et al., 1998; Sousa et al., 2013), t is the exercise time, τ is time constant of the PCr splitting at exercise onset (23.4 s) and M is the body mass (Zamparo et al., 2011).

Statistical analysis

Assuming a statistical power (β) 0.90, a large effect size (0.80) and a 0.05 overall level of significance, a 19-participant sample size seemed adequate for carrying out the current study (G*Power 3.1.9.7, Heinrich-Heine-Universität Düsseldorf, Germany). Mean plus SD were computed (GraphPad Prism 6) and data were checked for distribution normality with the Shapiro–Wilk test. The paired sample t-test was used to compare $\text{Ana}_{\text{recovery}}$ with Ana_{PCr} , and the efficiency method agreement was assessed by linear regression analysis and Bland–Altman plot. The significance level was set at 5%.

Results

The Fran workout duration was 192 ± 29 s, while the $\dot{V}O_{2\text{peak}}$, amplitude, time delay and time constant of the $\dot{V}O_2$ primary component during the recovery period were 41.8 ± 4.8 and 30.4 ± 4.1 $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$, and 7 ± 5 and 57 ± 14 s, respectively. Figure 2 displays the individual and average values of the anaerobic alactic contribution assessed through the two used methods, with no differences being observed between $\text{Ana}_{\text{recovery}}$ and Ana_{PCr} .

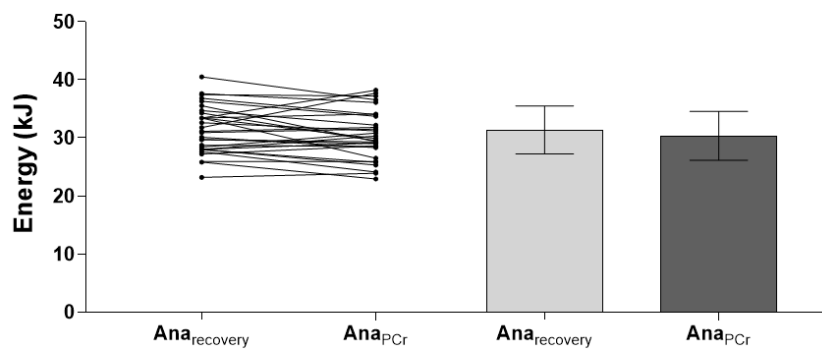


Figure 2. Individual and mean $\pm$ SD values of the $\dot{V}O_2$ off-kinetics fast component and the maximal phosphocreatine splitting in the contracting muscle ($\text{Ana}_{\text{recovery}}$ and Ana_{PCr} , respectively) methods for anaerobic alactic assessment.

The Bland–Altman plot, comparing differences between the anaerobic alactic contribution assessment methods and its average value, is reported in Figure 3. The average of the differences between methods was low and close to zero (0.29), indicating that they presented similar results. The corresponding limits of agreement (average $\pm$ 1.96 SD) ranged between -5.48 and 6.60 , indicating a small difference between the two methods for 95% of the subjects. In addition, the Bland–Altman regression showed no differences between $\text{Ana}_{\text{recovery}}$ and Ana_{PCr} for estimating anaerobic alactic contribution.

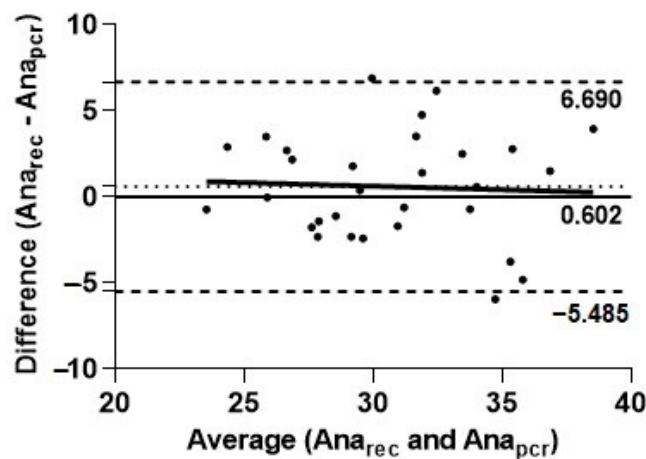


Figure 3. Bland–Altman plot comparing the two anaerobic alactic contribution assessment methods, with black dotted and dashed lines representing the 95% limits of agreement as well as the bias and linear regression (respectively).

Discussion

The alactic anaerobic energy source contributes significantly to the specific energy expenditure requirements of short-term resistance exercises (Reis et al., 2011). Nevertheless, its direct assessment through invasive methods, such as muscle biopsies, is expensive and complex, which is the reason why non-invasive alternatives are most frequently used (Gastin, 2001; Zamparo et al., 2011). In the current study, two methods of anaerobic alactic assessment along a CrossFit® short duration and maximal intensity workout were analyzed and compared, evidencing similar values. Although none could be considered as the gold standard approach, and since both have limitations (e.g., errors derived from a delay at the onset of $\dot{V}O_2$ recovery and the assumption of given value percentage of active muscle mass), the current study underlines the importance of estimating the anaerobic alactic contribution to assess the total energy expenditure (aerobic plus anaerobic systems) of a severe-intensity exertion. This will help researchers and coaches to evaluate their crossfitters accurately, with the aim to adjust the training plan accordingly to its specificity.

The post-exercise values of the $\dot{V}O_2$ fast component amplitude and time delay were lower than those reported for other exercise modes (e.g., running, rowing and swimming) (Sousa, Figueiredo, et al., 2015; Sousa et al., 2013). This may be due to the current study's higher exercise intensity and to a sport-specific

$\dot{V}O_2$ answer (Beneke et al., 2002; Gastin, 2001). Regarding the $\dot{V}O_2$ off-time constant, our results corroborate the literature conducted in other intensity domains (Monteiro et al., 2020; Sousa, Rodríguez, et al., 2015). The Anarecovery method was first introduced by Margaria et al., 1933, analyzing the post-excess $\dot{V}O_2$ in the recovery period, and was referred as alactic O_2 debt. Accordingly, most of the O_2 debt was then interpreted as the energy necessary to rebuild high-energy phosphate compounds (Di Prampero & Margaria, 1968). This interpretation has been confirmed in experiments in humans and on isolated muscle (in vivo) by assuming that PCr is rapidly resynthesized in the first 2 min after exercise (Harris et al., 1976; Karlsson, 1971; Piiper & Spiller, 1970). The advantage of the Ana_{recovery} method is that it does not interfere with muscle activity during the workout, maintaining the ecological validity of the measurements. The Ana_{recovery} values reported in the current study are lower than those reported for cycling (~40 kJ), boxing (~58 kJ) and running (~40 kJ) [3,8,20], but similar than those reported to swimming (~32 kJ) and kayaking (~32 kJ) (Beneke et al., 2002; Davis et al., 2014; Roberts & Morton, 1978). These differences could be attributed to different time durations and intensities of exercise, and the activation patterns of different muscle masses (Gastin, 2001; Sousa, Figueiredo, et al., 2015).

The Ana_{PCr} method considers that the energy derived from full utilization of PCr stores (during all-out efforts), which can be estimated assuming during the transition from rest to exhaustion, decreases in concentration ($18.55 \text{ mmol} \cdot \text{kg}^{-1}$) in relation to the active muscle mass (Capelli et al., 1998; Zamparo et al., 2011). The PCr stores assumed in the current study are in accordance with the decline in PCr measured by muscle biopsy at the end of exhaustive exercise (Bangsbo et al., 1990; Sahlin et al., 1979). Thus, in contrast to the muscle biopsy method (a highly invasive procedure), this method enables an easier and more ecological estimate of the anaerobic alactic contribution (Reis et al., 2011; Fernandes et al., 2018). The values of Ana_{PCr} reported in this study are similar to those described for swimming (~31 kJ), rowing (~31 kJ) and cycling (~29 kJ) events (Sousa, Figueiredo, et al., 2015; Sousa et al., 2013).

Although similar values were obtained using the two non-invasive methods, several limitations should be considered for both, and these could affect the

estimation of alactic anaerobic energy contributions. Regarding the Ana_{recovery} method, the fact that the $\dot{V}O_2$ fast component is independent of lactic acid removal from blood during the recovery period is still a matter of debate (Gastin, 2001). In addition, a forced apnea during muscle contractions at the end of the workout will likely induce an augmented expiration, increasing post-workout $\dot{V}O_2$ (Reis et al., 2011; Fernandes et al., 2018). There are variables that can change the values obtained by the Ana_{PCr} method, such as the percentage of active muscle mass, the associated time constant of $\dot{V}O_2$ on-response at the muscle level and the concentration of PCr per kilogram of wet muscle (Sousa, Figueiredo, et al., 2015; Zamparo et al., 2011).

The possibility of determining the anaerobic alactic contribution is necessary to adequately assess the total energy expenditure and to relate it to high-intensity CrossFit® workout performance. In addition, CrossFit® researchers, coaches and practitioners should better understand its metabolic demands if they wish to set accurate energetic training goals with the aim of specific workout adaptations. Although there are some caveats regarding both methods, considering the absence of other (non-invasive) approaches, it is still important to estimate this variable in these types of efforts.

Conclusions

In the current study, no differences in anaerobic alactic contribution were observed between the two investigated methods, suggesting that both methods can be utilized to estimate anaerobic alactic contribution in a specific CrossFit® workout performed at maximal exertion. The advantage of determining the alactic anaerobic contribution is to maintain the ecological validity of the measurements, consequently increasing the applicability of the results. Future studies should evaluate different CrossFit® workouts performed at maximum intensity (e.g., Isabel and Grace) to clarify the eventual differences between the two methods.

Chapter 5

Sex-related differences in the acute physiological response to high-intensity workout

Manoel Rios,¹ Ricardo Cardoso,¹ Victor Machado Reis,^{2,3} Daniel Moreira-Gonçalves,^{4,5} David B. Pyne,⁶ and Ricardo J. Fernandes¹

¹Center of Research, Education, Innovation and Intervention in Sport, Faculty of Sport and Porto Biomechanics Laboratory, Faculty of Sport, University of Porto, Porto, Portugal

²Department of Sport Sciences, Exercise and Health, University of Trás-os-Montes e Alto Douro, Vila Real, Portugal

³Research Center in Sports Sciences, Health Sciences and Human Development, Vila Real, Portugal

⁴Research Center in Physical Activity, Health and Leisure, Faculty of Sport, University of Porto, Portugal

⁵Laboratory for Integrative and Translational Research in Population Health, Porto, Portugal

⁶Research Institute for Sport & Exercise, University of Canberra, Canberra, Australia

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Abstract

We compared responses to a short Fran CrossFit® session (consisting of three rounds of 21, 15 and 9 front squat to press overhead and pull-ups) between sexes to evaluate differences in acute exercise effects. Twenty-five (15 males and 10 females) trained participants performed a prescribed Fran session at maximal exertion. Cardiorespiratory variables were assessed at baseline, during and post-exercise. The rating of perceived exertion, blood pressure, blood lactate and glucose concentrations were measured at baseline and in the recovery period. The males completed Fran session in less time (males 177 ± 15 vs females 206 ± 27 s; mean $\pm$ SD), resulting in higher peak oxygen uptake values (50.1 ± 3.3 vs 46.4 ± 2.2 mL·kg⁻¹·min⁻¹) and percentage heart rate (96 ± 3 vs 93 ± 1 %) compared to females. In addition, elevated systolic blood pressure (males 154 ± 8 vs females 149 ± 10 mmHg) and blood lactate (15.7 ± 1.7 vs 14.6 ± 2.0 mmol·L⁻¹) values were observed in both sexes post-exercise. The substantial metabolic demands associated with a Fran session can yield similar elevations in cardiorespiratory and hemodynamic responses in both sexes, meeting the criteria for developing cardiorespiratory fitness.

Key words: oxygen uptake; blood pressure; blood lactate; recovery

Introduction

Cardiorespiratory fitness measured as maximal exercise capacity is an established predictive marker of cardiovascular disease and all-cause mortality (Clarke et al., 2017). Improvements in maximal exercise capacity are primarily attributed to central adaptations (stroke volume), whereas peripheral adaptations (oxidative capacity) contribute far less (Clarke et al., 2017; Goodman et al., 1999). Conversely, when discussing improvements in submaximal cardiorespiratory fitness, these alterations are closely associated with peripheral adaptations (Clarke et al., 2017; Goodman et al., 1999). Maximal and/or peak oxygen uptake ($\dot{V}O_2$) is commonly used to assess cardiorespiratory fitness and functional capacity, providing valuable insights into the maximal workload that individuals can sustain during physical exertion (Lopes et al., 2022; Poole & Jones, 2012). In addition, evaluation of respiratory parameters, blood lactate concentration ($[La^-]$) and blood pressure is essential to characterize the acute physiological impact (Forte et al., 2022; Lopes et al., 2022; Rios et al., 2023) and consequently control chronic exercise adaptations (Gripp et al., 2021).

High-intensity interval exercise sessions of maximal to supramaximal intensities have a similar or even more substantial impact on cardiorespiratory fitness and metabolic adaptations than traditional continuous moderate-intensity training (Gillen & Gibala, 2018; Gripp et al., 2021). These findings underscore the effectiveness of short-duration, high-intensity exercise in inducing favourable exercise adaptations (Gripp et al., 2021; Tabata et al., 1997). However, most high-intensity interval exercise primarily involves cyclical modes of exercise like running or cycling to elicit cardiovascular adaptations (Gillen & Gibala, 2018; Tabata et al., 1997), but strength adaptations are often limited. In contrast, high-intensity functional exercise (e.g. CrossFit®) places emphasis on functional, multi-joint movements and incorporates both aerobic and strength exercises (Claudino et al., 2018; Rios et al., 2021). CrossFit® sessions are adaptable to diverse fitness levels and sex, enhancing muscle engagement more effectively than cyclical modes of exercise (Claudino et al., 2018). Similar to other high-intensity functional exercise modes, CrossFit® can improve body composition, muscle strength and cardiorespiratory fitness (McDougle et al., 2023).

However, CrossFit® workouts can also induce blood oxidative stress and raise markers of muscle damage, including interleukin-6 and creatine kinase (McDougale et al., 2023). The extent of these responses varies depending on factors including training intensity, duration, exercises and rest intervals (McDougale et al., 2023; Rios et al., 2023). Performance in CrossFit® is typically assessed by completion time or repetition count, with reference exercise (like Fran) commonly used for evaluating physical fitness (Rios, Becker, Monteiro, et al., 2024; Rios et al., 2023; Tibana et al., 2018). Reference workouts such as Fran are standardized in terms of external loads (e.g. males use 43 kg and females use 30 kg) and repetitions (e.g. 21-15 and 9) to facilitate consistent comparisons of performance among athletes and across various settings worldwide, irrespective of the location or setting in which they are executed (Rios, Becker, Cardoso, et al., 2024; Rios et al., 2023). The Fran session has been studied extensively, revealing elevated levels of $[La^-]$, glucose levels, heart rate (HR), and peak $\dot{V}O_2$, coupled with a high rating of perceived exertion (RPE) across its three rounds (Rios et al., 2023; Tibana et al., 2018). Currently, there is a scarcity of studies that analyze the comprehensive physiological impact of the Fran routine and magnitudes of difference between male and female.

Physiological factors influence physical fitness differences between males and females given distinct strength and endurance predispositions (Hottenrott et al., 2021; Howden et al., 2015). For example, males typically have a 10% higher maximal $\dot{V}O_2$ due to their greater heart size, blood volume and hemoglobin than females (Coe & Astorino, 2023; Howden et al., 2015). In addition, sex differences in oxidative capacity and fatigue tolerance are evident (Coe & Astorino, 2023). These distinctions are likely linked to a reduced reliance on non-oxidative metabolism during exercise in females relative to males (Coe & Astorino, 2023; Hottenrott et al., 2021). However, both groups have demonstrated comparable results in terms of movement economy (Timón et al., 2019). These inherent physiological variations may contribute to sex differences in the adaptive response to high-intensity exercise (Coe & Astorino, 2023; Howden et al., 2015), as the acute exercise response underpins the chronic response. The acute response to a high-intensity exercise session like a Fran

session reveal nuances or variations in this pattern. Current CrossFit® training practices often rely heavily on research conducted primarily on male athletes (Leitão et al., 2021; Rios, Becker, Cardoso, et al., 2024; Tibana et al., 2018). Consequently, female athletes may be expected to respond similarly to male, however, is this is not the case inaccurately prescribed training may not fully address their unique physiological (e.g cardiovascular response) needs. Prioritizing research on female physiology and exploring sex differences in response to CrossFit® training, we can gain valuable insights into how females differ from males in adapting to this type of exercise. This knowledge can then inform more tailored training methodologies for female athletes to enhance their exercise performance.

Despite the high energy demands of CrossFit® sessions, few studies have investigated the effects of selected CrossFit® exercises on physiological variables including $\dot{V}O_2$, $[La^-]$, perceived exertion and HR in real-world contexts (Forte et al., 2022; Rios, Becker, Monteiro, et al., 2024; Rios et al., 2023; Tibana et al., 2018). Moreover, data regarding blood pressure responses during these CrossFit® exercises are scarce, necessitating further investigation (Forte et al., 2022). Given CrossFit's increasing popularity among both sexes, with over 15,000 affiliated training centers and a community of 5 million crossfitters (Meier et al., 2023), it is also crucial to explore potential sex differences in these physiological responses, contributing to a better understanding of the sport and for optimal exercise recommendations. The aim of the study was to assess the cardiorespiratory, hemodynamic and metabolic responses during a high-intensity, short-duration CrossFit® Fran session in trained crossfitters. We also sought to compare these responses between sexes to gain insights into the contrasting acute effects to exercise. Our hypothesis was that a specific CrossFit® session meets the criteria for developing cardiorespiratory fitness in healthy adults.

Materials and methods

Participants

A sample of 25 trained adult participants (15 males and 10 females) who engaged in at least five CrossFit® training sessions per week participated in the

study. Table 1 presents their age, anthropometric and physiological characteristics. Recruitment was conducted through announcements at local CrossFit® gyms, with participants meeting the following criteria: (i) more than three years of CrossFit® practice; (ii) no history of cardiopulmonary or intestinal diseases and no musculoskeletal disorders; (iii) age between 18-40 years; and (iv) clearance to exercise according to the Physical Activity Readiness Questionnaire. Participants were instructed to abstain from caffeine and alcohol for 24 h before testing, avoid exercise 48 h before experimental sessions, and maintain their regular diet. Informed consent was obtained from all individual participants included in the study. The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Ethics Committee (CEFADE212019) and the guidelines of the World Medical Association for research on humans.

Design and procedures

All tests were performed in a gym facility under the same environmental conditions (23°C ambient temperature, 60% humidity and between 8-12 a.m.) and supervised by one experienced researcher. Body mass and height were obtained on arrival before the experimental session using a digital scale with a built-in stadiometer (SECA, model 220). Participants remained seated for 10 min before their resting $\dot{V}O_2$, HR, blood pressure, rating of perceived exertion (RPE), $[La^-]$ and glucose concentrations were measured. After a 5 min warm-up period for joint mobility and Fran specific exercises with low loads, each participant performed the exercises at maximal exertion, with $\dot{V}O_2$ and HR measured continuously during Fran session. $\dot{V}O_2$, HR, $[La^-]$, glucose, blood pressure and RPE responses were also measured immediately after, 5- and 30-min post-exercise.

Fran consists of three rounds with repetitions decreasing from 21-15-9, with each round including thrusters (combining front squats and overhead presses) and pull-ups. Males use a constant weight of 43 kg and females a 30 kg weight (Rios et al., 2023). For thrusters, participants lift a barbell from the floor into a front rack position, perform a deep squat, and smoothly transition into an overhead press without pausing. In pull-ups, participants start hanging from a

standard pull-up bar with arms fully extended and feet off the ground. They pull themselves up until their chin clears the bar before returning to the starting position. All evaluations of Fran sessions were supervised to ensure participants met the required intensity (no breaks) and completed the specified number of repetitions. Performance time was quantified using a Seiko stopwatch (Yokohama, Japan).

Respiratory and pulmonary gas exchange data were measured breath-by-breath at rest, during the Fran session, and post-exercise using a K4b² telemetric portable gas analyzer (Cosmed, Rome, Italy) calibrated using the manufacturer instructions with gases of known concentrations. The highest $\dot{V}O_2$ value from Fran session was defined as their peak $\dot{V}O_2$ and to determine the post-exercise $\dot{V}O_2$, the bi-exponential model was computed using VO2FITTING software for data analysis and treatment, as well as for editing and modelling participants' responses (Rios et al., 2022):

$$\dot{V}O_2(t) = A_0 - H(t - T_{D_p}) A_p (1 - e^{-(t - T_{D_p})/\tau_p}) - H(t - T_{D_{sc}}) A_{sc} (1 - e^{-(t - T_{D_{sc}})/\tau_{sc}})$$

where $\dot{V}O_2(t)$ represents the relative $\dot{V}O_2$ at the time t , A_0 is the $\dot{V}O_2$ at rest, H represents the Heaviside step function, A_p and A_{sc} , τ_p and τ_{sc} , T_{D_p} and $T_{D_{sc}}$ are the amplitude, time constant and time delay of the $\dot{V}O_2$ fast and slow components (Rios et al., 2022) HR was measured continuously by a Polar T34 Heart Rate Transmitter (Polar, Kempele, Finland), that telemetrically emitted the data to the K4b2 portable unit. The equation used to calculate the predicted maximal HR (HRmax) for each participant and to which the HR data obtained from the Fran session were compared was $208 - 0.7 \times \text{age}$ (Tanaka et al., 2001).

Systolic (SBP) and diastolic (DBP) blood pressures were measured on the left arm, with the cuff applied approximately 2.5 cm from the forearm. Participants were seated comfortably with their arms and hands resting on the table, avoiding movement and talking during measurements. Each participant's blood pressure was recorded three times, with a 30 s break between readings. The average of these three measurements was used to obtain the criterion value. Measurements were taken at baseline, immediately after Fran session and 5

min post-exercise using an automatic blood pressure monitor (OMRON, model HEM-705CP, Chicago, USA). Mean arterial pressure (Meaney et al., 2000) and double product (Jouven et al., 2005) were calculated using the following formulas: mean arterial pressure = $DBP + (SBP - DBP)/3$ and double product = $HR \times SBP$. To estimate participants' myocardial $\dot{V}O_2$ (Prado Dantas et al., 2018), the following equation was applied: myocardial $\dot{V}O_2 = (\text{double product} \times 0.0014) - 6.37$.

Capillary blood samples (5 μ L) were collected from the earlobe at baseline, immediately after Fran session and 5 min post-exercise for $[La^-]$ and glucose assessment using a Lactate Pro 2 (Arkay, Inc, Kyoto, Japan) and Accu-Chek Aviva (Mannheim, Germany) analyzers. The RPE was determined at baseline, immediately after Fran session and 30 min post-exercise using a Borg scale ranging from 6 to 20 (from very, very light to very and very heavy). To ensure accurate interpretation and consistent reporting, the RPE scale was explained individually to the participants according to the recommendations

Statistical analysis

All statistical calculations were completed using GraphPad Prism 6 (GraphPad Software, Boston, Massachusetts USA), with mean and standard deviation (SD) values for descriptive analysis. The Shapiro–Wilk test was used to assess data normality and/or two-sided 95% confidence interval reported for all variables. The independent sample t-test was applied to compare male and female characteristics, cardiorespiratory, hemodynamics, metabolic and perceived exertion variables. Repeated-measures analysis of variance (with a Bonferroni post hoc test) was applied to compare the cardiorespiratory, hemodynamics, metabolic and perceived exertion variables at different time points. The effect size was computed with Cohen's d and interpreted as follows: trivial if $|d| < 0.2$, medium if $0.2 > |d| < 0.5$, and large if $|d| \geq 0.5$. Statistical significance was set at 5%.

Results

Table 1 presents the anthropometric and physiological characteristics of the participants, with results showing that males had higher body mass and height

than females. The overall mean time to complete Fran session was 189 ± 28 s, ranging 177 to 199 s. Participants had a mean peak $\dot{V}O_2$ of 48.6 ± 3.4 mL·kg⁻¹·min⁻¹ and peak HR of 184 ± 6 b·min⁻¹, attaining 95% of their HRmax during Fran session.

Table 1 Anthropometric and physiological characteristics of the participants engaged in the current study.

Variables	Total (n = 25)	Males (n = 15)	Females (n = 10)	p
Age (years)	28.0 ± 5.3	29.2 ± 5.8	25.9 ± 4.1	0.135
Height (cm)	171.0 ± 8.3	176.3 ± 5.6	163.1 ± 4.2*	0.001
Body mass (kg)	75.6 ± 10.3	82.4 ± 7.4	65.5 ± 2.8*	0.001
Body mass index (kg·[m ²] ⁻¹)	25.4 ± 1.9	26.2 ± 1.9	24.1 ± 1.3*	0.011
Maximal heart rate (b·min ⁻¹)	189 ± 4	188 ± 4	190 ± 3	0.112
CrossFit® training experience (years)	5.6 ± 1.7	5.5 ± 1.5	5.8 ± 2.2	0.742

* Difference to males. Mean ± SD and probabilities (p).

During the Fran session and in the post-exercise period, cardiorespiratory, hemodynamic, and metabolic variables remained elevated compared with baseline (Table 2). Perceived exertion was significantly higher 30 min post-exercise compared to baseline ($p = 0.001$; 6 ± 0 vs 16 ± 1), with no significant differences immediately after the Fran session (16 ± 1).

Table 2 Overall physiological demands of Fran at baseline, during and at different post-exercise moments.

Variable	Baseline	Fran	0 min	5 min
Oxygen uptake (mL·kg ⁻¹ ·min ⁻¹)	6.8 ± 0.8 [6.5-7.1]	39.4 ± 2.0 * [38.5-40.2]	---	22.0 ± 3.0 * + [21.0-23.0]
Carbon dioxide production (L·min ⁻¹)	0.6 ± 0.1 [0.5-0.6]	3.3 ± 1.0 * [3.1-4.0]	---	2.3 ± 0.5 * + [2.1-2.5]
Respiratory frequency (b·min ⁻¹)	18.0 ± 2.0 [16.8-19.0]	53.3 ± 8.0 * [50.1-56.5]	---	36.0 ± 6.4 * + [33.2-38.4]
Minute ventilation (L·min ⁻¹)	18.4 ± 3.4 [17.3-20.1]	109.6 ± 24.0 * [99.7-119.4]	---	80.2 ± 18.0 * + [72.9-87.5]
Heart rate (b·min ⁻¹)	82 ± 10 [78-86]	178 ± 5 * [176-180]	---	131 ± 14 * + [124-136]
Systolic blood pressure (mmHg)	118 ± 8 [114-121]	---	152 ± 10 * [148-156]	130 ± 6 * # [128-133]
Diastolic blood pressure (mmHg)	79 ± 2 [78-80]	---	88 ± 4 * [87-90]	81 ± 2 * # [80-82]
Mean arterial pressure (mmHg)	92 ± 3 [90-93]	---	110 ± 4 * [108-112]	97 ± 2 * # [96-98]
Double product (mmHg·b·min ⁻¹)	9666 ± 1304 [9128-10205]	---	26630 ± 1870* [25858-27402]	16953 ± 1966* # [16141-17765]
Myocardial oxygen uptake (mL·100 g LV·min ⁻¹)	7.2 ± 2.0 [6.4-8.0]	---	31.0 ± 2.6 * [30.0-32.0]	17.3 ± 3.0 * # [16.2-18.5]
Blood lactate (mmol·L ⁻¹)	1.5 ± 0.4 [1.4-1.7]	---	10.3 ± 2.0 * [9.5-11.1]	15.2 ± 1.8 * # [14.5-16.1]
Blood glucose (mg·dL ⁻¹)	94 ± 8 [91-97]	---	121 ± 13 * [116-126]	132 ± 14 * # [126-138]

* Differences from baseline ($p \leq 0.05$). + Differences from Fran ($p \leq 0.05$). # Differences immediately

post-exercise ($p \leq 0.05$). Mean $\pm$ SD of males and females combined and [95% confidence intervals].

When comparing the sexes, males completed Fran session in less time (177 ± 15 vs 206 ± 27 s; $p = .006$, $d = 1.3$), resulting in higher peak $\dot{V}O_2$ (50.1 ± 3.3 vs 46.4 ± 2.2 mL $\cdot$ kg $^{-1}\cdot$ min $^{-1}$; $p = .015$, $d = 1.3$) and HR (187 ± 6 vs 180 ± 3 b $\cdot$ min $^{-1}$; $p = .039$, $d = 1.5$) than females. The percentage values of HRmax (96 ± 3 vs 93 ± 1 %; $p = .003$, $d = 1.3$) was also higher in the males. Comparisons of cardiorespiratory, hemodynamic and metabolic responses values at baseline, during Fran and post-exercise in the same sex, and between sexes, at the corresponding time points are shown in Figures 1, 2 and 3 (respectively). Cardiorespiratory responses to Fran session were similar in both sexes, showing increases in $\dot{V}O_2$, carbon dioxide production, respiratory frequency, minute ventilation and HR during Fran session and 5 min post-exercise (Figure 1).

However, males exhibited significantly higher $\dot{V}O_2$ during the Fran session (40.0 ± 1.8 vs 38.4 ± 2.0 mL $\cdot$ kg $^{-1}\cdot$ min $^{-1}$; $p = 0.042$, $d = 1.2$), as well as elevated levels of carbon dioxide production (3.7 ± 0.4 vs 2.7 ± 0.2 L $\cdot$ min $^{-1}$; $p = 0.001$, $d = 3.2$) and minute ventilation (123.9 ± 18.8 vs 88.1 ± 10.9 L $\cdot$ min $^{-1}$; $p = 0.001$, $d = 1.9$) during both the Fran session and the recovery period (carbon dioxide production: 2.6 ± 0.4 vs 1.8 ± 0.3 L $\cdot$ min $^{-1}$; $p = 0.001$, $d = 3.2$; minute ventilation: 89.7 ± 16.1 vs 66.0 ± 7.1 L $\cdot$ min $^{-1}$; $p = 0.001$, $d = 0.1$) than females (Figure 1). In contrast, no significant differences were observed in hemodynamic, metabolic and perceived exertion variables between sexes (Figures 2 and 3).

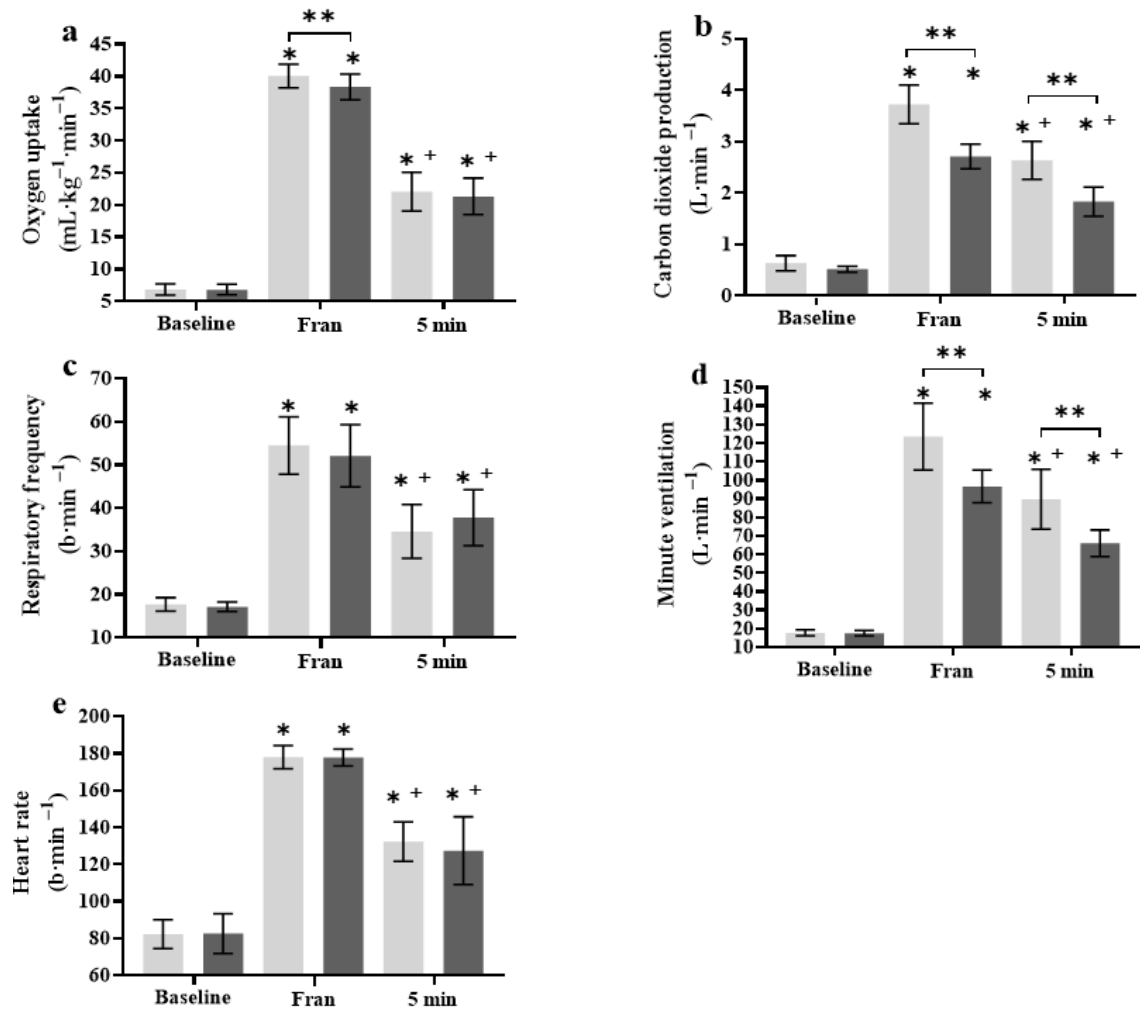


Figure 1. Cardiorespiratory variables assessed during baseline, Fran and post-exercise for males (light grey) and females (dark grey). * Differences from baseline in the same sex ($p \leq 0.05$). + Differences from Fran in the same sex ($p \leq 0.05$). ** difference between the sexes at the same time point ($p \leq 0.05$). Mean $\pm$ SD.

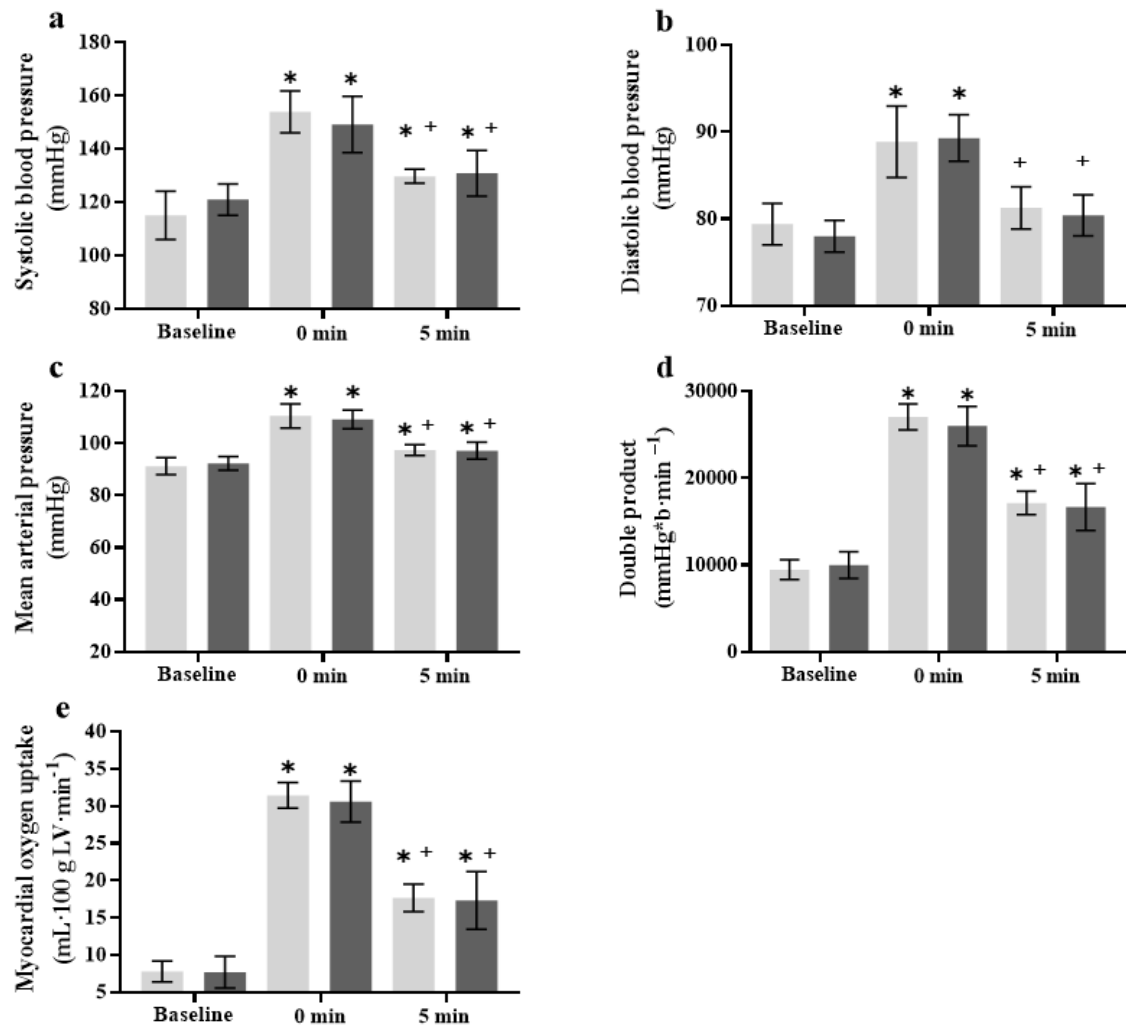


Figure 2. Hemodynamics variables assessed during baseline and post-exercise for males (light grey) and females (dark grey). * Differences from baseline in the same sexes ($p \leq 0.05$). + Differences from Fran in the same sexes ($p \leq 0.05$). Mean $\pm$ SD.

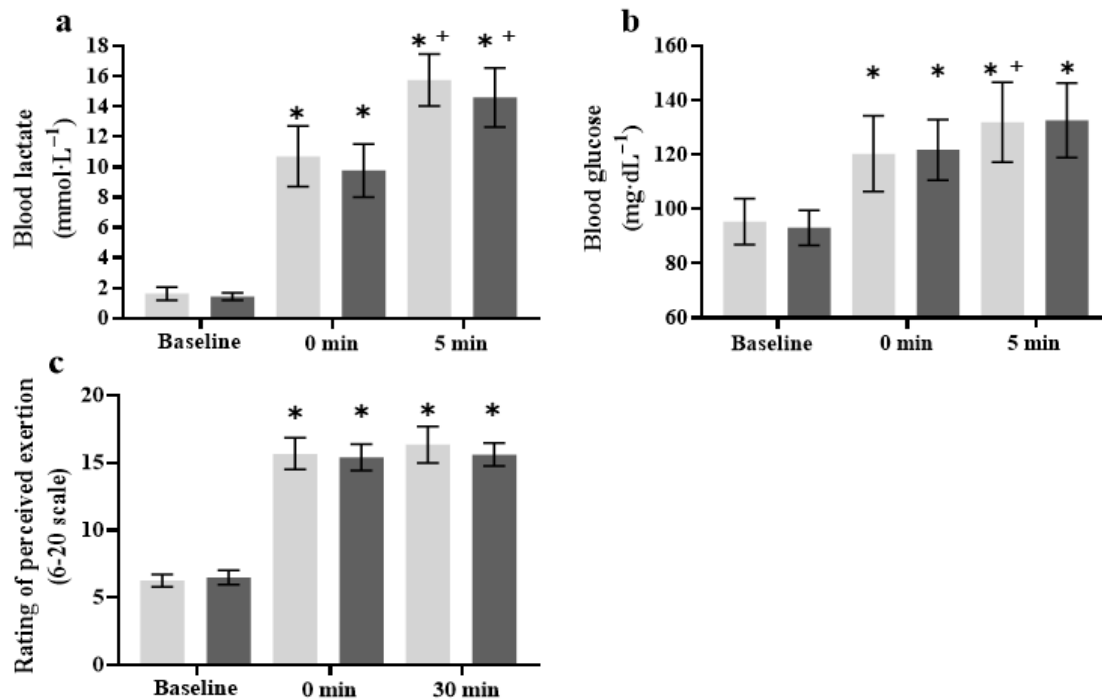


Figure 3. Metabolic variables and perceived effort assessed during baseline and post-exercise for males (light grey) and females (dark grey). * Differences from baseline in the same sexes ($p \leq 0.05$). + Differences from Fran in the same sexes ($p \leq 0.05$). Mean $\pm$ SD.

Discussion

The main findings of this study were: (i) a single CrossFit® Fran session induced significant elevations in cardiorespiratory responses ($\dot{V}O_2$ and HR) both during and post-exercise; (ii) the Fran session increased both blood pressure and double product, which remained elevated 5 min post-exercise; (iii) these increased cardiorespiratory and hemodynamic responses during exercise were reflected in increased concentrations of $[La^-]$ and glucose, coupled with heightened self-reported perceived exertion post-exercise; (iv) males exhibited higher values in mean and peak $\dot{V}O_2$, and peak HR during Fran session than females. Our data indicates that a short-duration (~3 min) CrossFit® Fran session elicited cardiorespiratory demand commensurate with recommendations for enhancing cardiovascular fitness. The high hemodynamic and metabolic demands of the Fran session confirm its utility and effectiveness

in prescribing exercises to elicit positive acute adaptations, with a greater peripheral response in males compared to females.

The mean and peak $\dot{V}O_2$ and HR values during Fran session, along with utilizing ~95% of HRmax to complete the exercise, align with guidelines for improving cardiorespiratory fitness (Garber et al., 2011). Our results correspond with previous studies assessing $\dot{V}O_2$ (Rios et al., 2023) and HR (Leitão et al., 2021; Tibana et al., 2018) during a Fran session, indicating higher values than maximal effort cycling sprint interval training (Freese et al., 2013; Williams & Kraemer, 2015) and cycling high-intensity interval exercise (Järvinen et al., 2022). The elevated $\dot{V}O_2$ and HR values observed during Fran session may be attributed to the overall exercise volume and the absence of breaks, facilitating an elevated demand on the cardiac, vascular and respiratory systems. In addition, the movement of the arms and trunk demands a significant O_2 requirement compared with cycling, where they have a lower contribution to the total exercise $\dot{V}O_2$ (Hill et al., 2003). In fact, efforts to complete an exercise session in the shortest time yield an increase in minute ventilation, respiratory frequency and carbon dioxide production (Tipton et al., 2017). The increase in minute ventilation is a result of both heightened tidal volume and an elevated respiratory frequency during exercise (Guenette & Sheel, 2007; Tipton et al., 2017). Moreover, carbon dioxide production is highly related to minute ventilation since this latter variable allows the CO_2 removal, preventing or constraining the perturbation in arterial blood gas and acid-base status (Poole & Jones, 2012).

Cardiorespiratory function remained elevated during the recovery period compared with baseline values, consistent with resistance exercise (Rios, Becker, Monteiro, et al., 2024; Thornton & Potteiger, 2002). The high intensity and great volume of muscle contractions (90 repetitions of thrusters plus pull ups) during Fran session contributed to the marked increase in $\dot{V}O_2$ post-exercise compared with baseline (Rios et al., 2023). This increase can possibly be attributed to several factors, including the restoration of muscle adenosine triphosphate and creatine phosphate reserves, the replenishment of O_2 reserves in the blood and muscles (Thornton & Potteiger, 2002). Moreover, the high values of minute ventilation ($\sim 80 \text{ L} \cdot \text{min}^{-1}$) during the recovery period are

additional evidence of the remarkable disruption of homeostasis after a single Fran session of maximal effort (Thornton & Pottleiger, 2002). This increased minute ventilation may also be interpreted as a compensatory mechanism aimed at restoring the normal pH that may have been disturbed by the accumulation of high $[La^-]$ levels post-exercise ($\sim 15 \text{ mmol}\cdot\text{L}^{-1}$). In this study, the cardiovascular intensity achieved during Fran session was $\sim 95\%$ of HRmax, indicating a greater of hemodynamic stress when compared to other studies evaluating blood pressure after Fran session and high-intensity functional exercises performed at maximal effort (Forte et al., 2022). These results can be explained by the differences in the duration and intensity of CrossFit® exercises, coupled with the lack of inter-round rest (which intensifies mechanical occlusion of blood flow during Fran session). These factors collectively contribute to an increase in cardiovascular function, affecting plasma volume, cardiac output and stroke volume (MacDonald, 2002). While not the main focus of this study, the observed increases in post-exercise $\dot{V}O_2$ could potentially facilitate greater calorie expenditure at rest, offering potential benefits for weight control among crossfitters.

The Fran session elicited an immediate post-exercise increase in $[La^-]$ level, indicating a substantial contribution from the anaerobic pathway. This outcome aligns with previous studies that have assessed the impact of a Fran session on $[La^-]$ levels (Leitão et al., 2021; Rios et al., 2023; Tibana et al., 2018) and compared to high-intensity functional exercises (Forte et al., 2022; Rios et al., 2021). However, these values were higher than those observed in high-intensity interval exercises (Maté-Muñoz et al., 2018). The Fran session demands total effort and a higher energy/time ratio, intensifying the contribution of the anaerobic pathway, thereby contributing to an increase in metabolic acidosis. In support of this assertion, the anaerobic contribution during Fran session increased carbohydrate metabolism evidenced by increased glucose at the muscular level (see Table 2). This increase in glucose is consistent with previous examination of the Fran session (Rios et al., 2023), and higher than those reported to high-intensity functional exercises (Rios, Becker, Cardoso, et al., 2024). In summary, it appears that $[La^-]$ and glucose responses depend on both the duration of effort and structure of the CrossFit® exercise session.

Efforts performed at maximal intensity yielded higher levels of $[La^-]$ and glucose, indicating increased reliance on anaerobic metabolism. Perceived exertion of the participants in this study was "hard" or "very hard", consistent with other studies employing the Borg scale to assess the intensity of Fran session (Leitão et al., 2021; Rios et al., 2023; Tibana et al., 2018) and high-intensity functional exercises (Maté-Muñoz et al., 2018; Rios, Becker, Cardoso, et al., 2024). A higher RPE value, combined with elevated metabolic responses after an intense Fran session, indicates the presence of adequate stimuli to promote resistance adaptation (Rios et al., 2023).

Sex differences can influence the pattern of adaptation to acute and chronic exercise (Coe & Astorino, 2023; Howden et al., 2015). A recent study (Forte et al., 2022) demonstrated no differences in the acute physiological responses (e.g. HR, $[La^-]$ and blood pressure) between males and females during and after CrossFit® exercises (like Cindy and Diane). In contrast, a longitudinal study (Poderoso et al., 2019) reported increased testosterone and decreased cortisol levels in males during CrossFit® training, with no hormonal changes evident in females. However, this study did not explore potential associations between these hormonal changes and other physiological adaptations. Our study showed similar physiological responses in males and females (when overall results were compared), however differences between sexes became apparent when data were separated. We observed a marked difference in the total duration of the Fran session, with males completing it in mean of 177 s compared to females who took 206 s.

In addition, the males had higher peak $\dot{V}O_2$ and HR levels than females. Females generally demonstrate relatively lower maximal $\dot{V}O_2$ values than males when cycling or running (Lepers, 2019). This difference has often been attributed to central factors, such as the presence of a smaller heart and lower hemoglobin mass in females, which can limit their capacity to effectively deliver oxygen to skeletal muscles (Howden et al., 2015). Considering the absence of differences in hemodynamic and metabolic function between the sexes, it appears the variation in physiological response between males and females during an acute Fran session is influenced by peripheral effects. In fact, males generally possess a higher ATP synthesis capacity to sustain muscle

contraction during prolonged efforts, attributed to their greater aerobic and anaerobic power. This is primarily due to their elevated glycolytic capacity, emphasizing their superior anaerobic capability compared to females (Jaworowski et al., 2002).

Assessing benchmark sessions like Fran is vital, as they serve as standard exercises used by CrossFit® professionals to gauge fitness levels, featuring specific load parameters and movement patterns (Meier et al., 2023). Our findings demonstrate that the Fran session is indeed challenging, with males exhibiting slightly higher peripheral responses than females. These results carry practical significance, indicating that researchers and coaches can incorporate the Fran session performed at maximal effort into a comprehensive plan to assess and monitor the training status of crossfitters throughout a CrossFit training season.

Several limitations of the current study warrant acknowledgment. First, we acknowledge that exercise performance in females could be influenced by variations in menstrual cycle phases. However, since we did not collect this information, we were unable to address this issue. Secondly, it should be noted that these results are applicable primarily to trained individuals, and thus may not be directly transferable to untrained individuals. Longitudinal studies examining cardiorespiratory, hemodynamic and metabolic responses to multiple days of CrossFit® training, employing consistent methodologies, are essential for gaining a deeper insight into chronic physiological adaptations in individuals of varying sexes and CrossFit® experience levels.

Conclusion

A single session of Fran CrossFit® induces substantial elevations in cardiorespiratory and hemodynamic responses, along with increased post-exercise metabolic activity and perceived exertion, observed in trained crossfitters of both sexes. These pronounced physiological responses provide an effective means of enhancing maximal $\dot{V}O_2$ compared to more moderate exercise intensities. These outcomes offer valuable insights for coaches and CrossFit® participants, facilitating informed training planning and optimization. However, given the diverse range of workouts and activities within CrossFit®,

further research is warranted to comprehensively understand the physiological and performance effects associated with this fitness regimen.

Chapter 6

Assessment of Cardiorespiratory and metabolic contributions in an extreme intensity CrossFit® benchmark workout

Manoel Rios,¹ Klaus Magno Becker,¹ Filipa Cardoso,¹ David B. Pyne,² Victor Machado Reis,^{3,4} Daniel Moreira-Gonçalves,^{5,6} and Ricardo J. Fernandes¹

¹Center of Research, Education, Innovation and Intervention in Sport, Faculty of Sport and Porto Biomechanics Laboratory, Faculty of Sport, University of Porto, Porto, Portugal

²Research Institute for Sport & Exercise, University of Canberra, Canberra, Australia

³Department of Sport Sciences, Exercise and Health, University of Trás-os-Montes e Alto Douro, Vila Real, Portugal

⁴Research Center in Sports Sciences, Health Sciences and Human Development, Vila Real, Portugal

⁵Research Center in Physical Activity, Health and Leisure, Faculty of Sport, University of Porto, Portugal

⁶Laboratory for Integrative and Translational Research in Population Health, Porto, Portugal

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Abstract

Our purpose was to characterize the oxygen uptake kinetics ($\dot{V}O_2$), energy systems contributions and total energy expenditure during a CrossFit® benchmark workout performed in the extreme intensity domain. Fourteen highly trained male crossfitters, aged 28.3 ± 5.4 years, with height 177.8 ± 9.4 cm, body mass 87.9 ± 10.5 kg and 5.6 ± 1.8 years of training experience, performed the Isabel workout at maximal exertion. Cardiorespiratory variables were measured at baseline, during exercise and the recovery period, with blood lactate and glucose concentrations, including the ratings of perceived exertion, measured pre- and post-workout. The Isabel workout was 117 ± 10 s in duration and the $\dot{V}O_2$ peak was 47.2 ± 4.7 mL·kg⁻¹·min⁻¹, the primary component amplitude was 42.0 ± 6.0 mL·kg⁻¹·min⁻¹, the time delay was 4.3 ± 2.2 s and the time constant was 14.2 ± 6.0 s. The accumulated $\dot{V}O_2$ (0.6 ± 0.1 vs. 4.8 ± 1.0 L·min⁻¹) value post-workout increased substantially when compared to baseline. Oxidative phosphorylation (40%), glycolytic (45%) and phosphagen (15%) pathways contributed to the 245 ± 25 kJ total energy expenditure. Despite the short ~2 min duration of the Isabel workout, the oxygen-dependent and oxygen-independent metabolism energy contributions to the total metabolic energy release were similar. The CrossFit® Isabel requires maximal effort and the pattern of physiological demands identifies this as a highly intensive and effective workout for developing fitness and conditioning for sports.

Key words: Oxygen uptake; bioenergetics; total energy expenditure; crossfitters

Introduction

Quantifying the dynamic features of oxygen uptake ($\dot{V}O_2$) kinetics has gained popularity in human physiology as a means of identifying the mechanisms underlying the control of muscle $\dot{V}O_2$ during exercise (Poole & Jones, 2012; Whipp & Ward, 1990). Traditionally, the dynamic $\dot{V}O_2$ response to exercise has been studied in three intensity ranges, i.e., low-moderate (until the anaerobic threshold) (Robergs, 2014), heavy (above the anaerobic threshold) (Pringle et al., 2003) and severe (in the area in which maximal $\dot{V}O_2$ is achieved) domains (Gaesser & Poole, 1996). More recently, the extreme exercise domain has been proposed for performances leading to exhaustion before maximal $\dot{V}O_2$ is reached, with $\dot{V}O_2$ kinetics characterized by development of a fast component with insufficient time for the appearance of a discernible $\dot{V}O_2$ slow component (Hill et al., 2002). $\dot{V}O_2$ kinetics at low-severe exercise intensities have been well established in cyclic exercise modes including running, cycling, swimming and rowing (F. Cardoso et al., 2022; Poole & Jones, 2012; Pringle et al., 2002; Sousa, Rodríguez, et al., 2015).

CrossFit® is a multi-modal physical training program that covers functional movement patterns in a single high-intensity training session emphasizing strength and metabolic conditioning (Dominski et al., 2022). Improvements in metabolic capacity and lung function provided by CrossFit® are functions of the duration, type and intensity of exercise (Rios, Becker, et al., 2024; Rios, Zacca, et al., 2023; Tibana et al., 2018). To assess and monitor fitness while tracking changes in work capacity over time, CrossFit® has integrated standardized exercises known as benchmark workouts (Claudino et al., 2018; Meier et al., 2021). These benchmarks exhibit variations in specific exercise routines/composition, intensity, duration, number/type of exercises and rest periods (see Figure 1) (Meier et al., 2023). The manipulation of these parameters will ultimately affect the magnitude of the fitness and performance improvements, and the associated risk of overload (Rios, Zacca, et al., 2023; Tibana et al., 2018). Scoring methods typically involve achieving a total number of repetitions within a specified time frame (Meier et al., 2023). CrossFit® research is needed to uncover predictive variables for performance in benchmark workouts through conventional laboratory tests (Dexheimer et al.,

2019; Leitão et al., 2021; Zeitz et al., 2020). However, due to the specificity of these workouts, the application of traditional laboratory testing protocols is constrained, as the physiological demands diverge from those encountered in a real-world training context. It is worth noting that only a limited number of pre-established workouts have been systematically characterized, with Cindy (Forte et al. 2022; Kliszciewicz et al., 2017; Maté-Muñoz et al., 2018) and Fran (Leitão et al., 2021; Rios, Becker, et al., 2024; Rios, Zacca, et al., 2023; Tibana et al., 2018) benchmarks workouts standing out as the most extensively assessed.

CrossFit® benchmark workouts			
Barbara	Cindy	Nicole	Jackie
5 rounds (for time) 20 Pull-ups 30 Push-ups 40 Sit-ups 50 Air squats	Every min on the min (for 20 min) 5 Pull-ups 10 Push-ups 15 Air squats	Every min on the min (for 20 min) 400-m run Max pull-ups	For time 1000-m row 50 Thrusters (45/35 lb) 30 Pull-ups
Amanda	Diane	Fran	Angie
9-7-5 (reps for time) Muscle-ups Squat snatches (135/95 lb)	21-15-9 (reps for time) Deadlifts (225/155 lb) Handstand push-ups	21-15-9 (reps for time) Thrusters (95/65 lb) Pull-ups	For time 100 Pull-ups 100 Push-ups 100 Sit-ups 100 Air squats
Linda	Isabel	Grace	Helen
10-9-8-7-6-5-4-3-2-1 (reps for time) Deadlift (1½ bodyweight) Bench Press (bodyweight) Clean (¾ bodyweight)	For time 30 Snatches (135/95 lb)	For time 30 clean and jerks (135/95 lb)	3 Rounds (for Time) 400-m run 21 Kettlebell swings 12 Pull-ups
Chelsea	Nancy	Lynne	Eva
Every min on the min (for 30 min) 5 Pull-ups 10 Push-ups 15 Air squats	5 Rounds (for time) 400-m run 15 Overhead squats (95/65 lb)	5 rounds (as many reps as possible) Max bench press (bodyweight) Max pull-ups	5 Rounds (for time) 800-m run 30 Kettlebell swings 30 Pull-ups

Figure 1. Overview of exercises and structural elements in CrossFit® benchmark workouts.

Prior studies reveal an acute blood oxidative stress (Rios et al., 2021) response and heightened concentrations in the indirect blood markers of muscle damage, such as interleukin-6 and creatine kinase, post-CrossFit® sessions (Jacob et al., 2020; Kliszciewicz et al., 2015; Tibana et al., 2016). Diverse CrossFit® workouts correlate positively with elevated blood lactate concentrations ($[La^-]$), highlighting the impact of factors like workout intensity, duration, exercise variety and rest periods on physiological responses (Forte et al., 2022; Maté-Muñoz et al., 2018; Maté-Muñoz et al., 2017; Rios, Becker, et al., 2024; Rios, Zacca, et al., 2023). In CrossFit® workouts conducted at severe intensity, there is a substantial oxidative phosphorylation energy contribution that should be considered a vital element in the training process. In addition, the

optimization of various metabolic pathways is achievable depending on the total duration and performance (intermittent or continuous) strategy of the workout (Maté-Muñoz et al., 2018; Rios, Becker, et al., 2024; Rios, Zacca, et al., 2023). Furthermore, an observed reduction in muscle functional capacity underscores the dynamic nature of these workouts (Forte et al., 2022; Maté-Muñoz et al., 2018). Cardiorespiratory and bioenergetic assessments have been primarily assessed in well-controlled environments, particularly in exercise laboratories (Bellar et al., 2015; Butcher et al., 2015). The number of studies conducted on training and competition conditions is limited (Rios, Becker, et al., 2024; Rios, Zacca, et al., 2023). Studies not accounting for the oxygen-independent metabolism (glycolytic and phosphagen pathways) contribution at higher exercise intensities result in an underestimation of the total energy expenditure, which negatively impacts the overall understanding of the effects of specific workouts (Gastin, 2001).

Isabel stands as a timed CrossFit® benchmark workout, challenging participants to complete 30 snatch repetitions with a 61 kg barbell in the shortest time possible. Widely employed for evaluating performance improvements in crossfitters, this workout is renowned for its substantial muscular power demands (Peña et al., 2021). However, to gain a more comprehensive understanding of the effects of workout intensity on the specific training performance of crossfitters, more detailed physiological assessments, such as $[La^-]$ and cardiorespiratory parameters, are essential (Maté-Muñoz et al., 2018; Rios, Becker, et al., 2024; Rios, Zacca, et al., 2023; Tibana et al., 2018). The purpose of the current study was to characterize the $\dot{V}O_2$ kinetics, estimate the contribution of the different energy systems and calculate the total energy expenditure of the Isabel workout. We expected that the specific cardiorespiratory demands would be consistent with the extreme intensity domain classification.

Methods and methods

Participants

Fourteen highly trained male crossfitters of 28.3 ± 5.4 years old and with height 177.8 ± 9.4 cm, body mass 87.9 ± 10.5 kg, lean body mass $52.1 \pm 4.5\%$, fat

body mass $12.3 \pm 4.8\%$, body mass index 27.8 ± 2.2 and 5.6 ± 1.8 years of training experience volunteered to participate. Subjects were recruited if they had a CrossFit® training frequency of more than five times per week for a minimum of three years before the commencement of the study. Participants were contacted personally and selected based on the following eligibility criteria: (i) ability to perform the Isabel workout <2 min; (ii) age between 18-40 years; and (iii) eligible to exercise according to the Physical Activity Readiness Questionnaire. All crossfitters were provided with clear instructions to adhere to their typical nutritional habits and explicitly instructed to abstain from consuming alcohol and caffeine, as well as engaging in intense physical activity, in the 48 h prior to the test. Detailed information about the experimental procedures, associated risks, and the benefits of participation was provided to all volunteers. All experiments were approved by the local Ethics Committee (CEFADE212019), with participants reading and signing an informed consent form in accordance with the Declaration of Helsinki and guidelines of the World Medical Association for research with humans.

Experimental design

All assessments were conducted in a gym facility, maintaining consistent environmental conditions of 23 °C ambient temperature and 60% humidity. The assessments were supervised by an experienced CrossFit® researcher, ensuring meticulous and precise execution, thereby maintaining consistency and reliability across all participants. Initial measurements of body mass were obtained using the InBody 120 (Seul, Republic of Korea), while height was recorded using the Seca 222 stadiometer (Brussel, Belgium) immediately upon participants' arrival. A standardized 10 min warm-up, including joint mobility exercises and specific movements with low loads tailored for Isabel, was administered. Subsequently, each CrossFitter engaged in the Isabel workout, exerting maximal effort. Pulmonary gas exchange was monitored breath-by-breath throughout the baseline, during the workout and in post-workout phases using a K5 telemetric portable gas analyzer (Cosmed, Rome, Italy). Simultaneously, continuous heart rate data were captured by a telemetric heart rate monitor belt (Cosmed ANT+), transmitting information to the K5 portable unit (Figure 2).

During the recovery, subjects maintained a seated position for subsequent data collection. Capillary blood samples (5 μ L) were collected from a fingertip at baseline at the 1st, 3rd, 5th and 7th min post-workout. The initial sample was discarded to eliminate contaminants and ensure measurement accuracy. Capillary blood collection involved applying controlled pressure to the finger, minimizing volume variations for consistent results. Lactate concentration ($[La^-]$) and glucose levels were determined using the Lactate Pro analyzer (Arkay, Inc, Kyoto, Japan) and Accu-Chek Aviva analyzer (Mannheim, Germany), respectively. The participants' self-reported perceived exertion was assessed using the Borg scale ranging from 6 to 20 (from very, very light to very and very heavy) at both baseline and 30 min post-workout. To ensure accurate interpretation and consistent reporting, the rating of the perceived exertion scale was explained individually to the participants according to the recommendations (Borg, 1970).

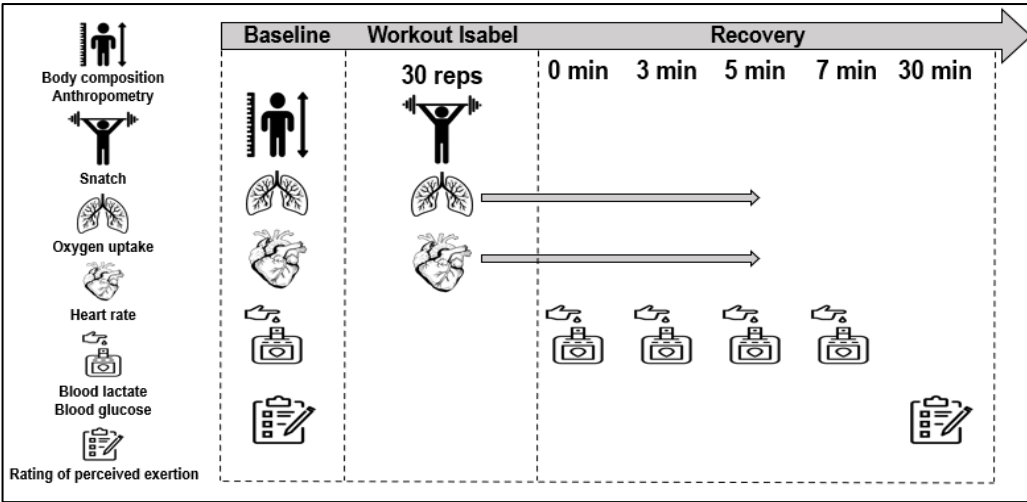


Figure 2. Workout Isabel data collection set-up.

Methodology

The $\dot{V}O_2$ peak and ventilatory variables' mean values were determined by analyzing the data from the final 30 s of exercise (Rios, Becker, et al., 2024). Data were carefully reviewed, and any breaths resulting from coughing or signal interruptions were excluded from the analysis (Reis et al., 2017; Rios et al., 2022). Only values within the range of mean $\pm$ 3 standard deviations were considered for further analysis. Subsequently, a smoothing process was applied using a moving average for three breaths and a temporal average for 10 s,

respectively (Vianna et al., 2011). For the estimation of $\dot{V}O_2$ kinetics parameters, a bootstrapping approach with 1000 samples was employed, with the exclusion of the cardiodynamic phase from the analysis (Koppo et al., 2002). The on-transient $\dot{V}O_2$ of Isabel's workout and the excess post-exercise $\dot{V}O_2$ were determined using both mono-exponential and bi-exponential models through the VO2FITTING software (Zacca et al., 2019):

$$\dot{V}O_2(t) = A_0 + H(t - T_{D_p}) A_p (1 - e^{-(t - T_{D_p})/\tau_p})$$

$$\dot{V}O_2(t) = A_0 - H(t - T_{D_p}) A_p (1 - e^{-(t - T_{D_p})/\tau_p}) - H(t - T_{D_{sc}}) A_{sc} (1 - e^{-(t - T_{D_{sc}})/\tau_{sc}})$$

where $\dot{V}O_2(t)$ represents the oxygen uptake normalized to body mass at time t , which is the baseline value for $\dot{V}O_2$, H denotes the Heaviside step function, A_p and A_{sc} are the amplitudes of the primary and slow component phases, whereas T_{D_p} and $T_{D_{sc}}$, τ_p and τ_{sc} are the corresponding time delays and time constants of the fast and slow components of $\dot{V}O_2$, respectively (Zacca et al., 2019). Accumulated $\dot{V}O_2$ was computed as the ratio of the time integral of net $\dot{V}O_2$ to the exercise duration (Rios, Becker, et al., 2024). An individual example of the $\dot{V}O_2$ kinetics during and post-exercise responses is presented in Figure 3.

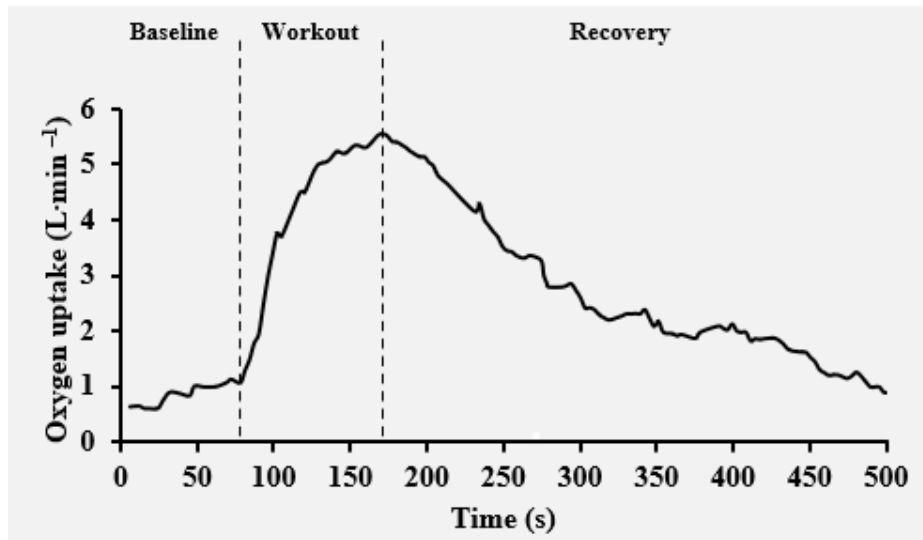


Figure 3. Example of the oxygen uptake kinetics as a function of time along the baseline, Isabel workout and recovery.

To assess the contribution of the oxidative phosphorylation energy system, the time integral of the net $\dot{V}O_2$ versus time relationship was examined (Rios, Becker, et al., 2024; Rios, Zacca, et al., 2023). The oxygen-independent

metabolism contribution was approximated as the sum of the energy derived from lactic acid production and phosphocreatine splitting in the contracting muscles (Rios, Becker, et al., 2024; Rios, Zacca, et al., 2023):

$$\text{Glycolytic pathway} = [\text{La}^-]_{\text{net}} \cdot \beta \cdot M$$

where $[\text{La}^-]_{\text{net}}$ is the peak accumulation of lactate after exercise, β is the constant for O_2 equivalent for lactate accumulation in the blood ($3 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{mM}^{-1}$) and M (kg) is the body mass of de CrossFitter (Zamparo et al., 2011; Rios, Zacca, et al., 2023). The phosphagen pathway contribution was estimated based on the maximal phosphocreatine splitting in the contracting muscle. This estimate assumed an energy equivalent of $0.468 \text{ kJ} \cdot \text{mM}^{-1}$ and a phosphate/oxygen ratio of 6.25 (Rios, Becker, et al., 2024; Rios, Zacca, et al., 2023):

$$\text{Phosphagen pathway} = \text{PCr} \cdot (1 - e^{-t/\tau}) \cdot M$$

where t represents the time duration, τ is the time constant of phosphocreatine splitting at the onset of workout (23.4 s), M (kg) denotes the mass of the participant and PCr is the assumed phosphocreatine concentration at rest, set at $18.5 \text{ mmol} \cdot \text{kg}^{-1}$ (Rios et al., 2022; Zamparo et al., 2011). Energy system contributions were quantified in kilojoules (kJ), assuming an energy equivalent of $20.9 \text{ kJ} \cdot \text{L}^{-1}$ (Rios, Zacca, et al., 2023; Sousa, Figueiredo, et al., 2015). The total energy expenditure during Isabel's workout was estimated by summing the contributions of the three energy systems (Sousa, Figueiredo, et al., 2015; Zamparo et al., 2011). To estimate metabolic power, energy expenditure was divided by the total duration (s) of the Isabel workout (Rios, Zacca, et al., 2023; Zamparo et al., 2011). Caloric expenditure is estimated by multiplying absolute $\dot{V}\text{O}_2$ by $5.05 \text{ kcal} \cdot \text{L}^{-1}$ (expressed in kJ by assuming an energy equivalent of $4.184 \text{ kJ} \cdot \text{L}^{-1}$) (Reis et al., 2017; Rios, Zacca, et al., 2023).

Statistical analysis

All calculations were completed using GraphPad Prism 6, with descriptive statistics presented as mean and standard deviation (SD). Data normality was checked through the Shapiro–Wilk test and repeated-measures ANOVA (with a Bonferroni post-hoc test) was applied to compare cardiorespiratory and

energetic variables at different time points. A paired sample *t*-test was applied to compare perceived exertion and metabolic variables before and after the workout. Based on a post-hoc analysis, a sample of 14 subjects, an effect size of 0.8 and a 0.05 overall level of significance, the statistical power (β) obtained was 0.80. The effect size was calculated using Cohen's *d* and interpreted as follows: trivial if $d < 0.2$, medium if $0.2 > d < 0.5$ and large if $d \geq 0.5$. The statistical significance level was set at 5%.

Results

The overall Isabel workout duration was 117 ± 10 s, with an exercise frequency of 0.3 ± 0.0 repetition/s. During the exercise, the $\dot{V}O_2$ peak, primary component amplitude, time delay and time constant values were 47.2 ± 4.7 and 42.0 ± 6.0 mL·kg⁻¹·min⁻¹, 4.3 ± 2.2 and 14.2 ± 6.0 s (respectively). The cardiorespiratory values at baseline, during the Isabel workout and at recovery are presented in Figure 4. The accumulated $\dot{V}O_2$ ($p = 0.001$, $d = 5.8$), minute ventilation ($p = 0.001$, $d = 7.6$), respiratory frequency ($p = 0.001$, $d = 6.2$), tidal volume ($p = 0.001$, $d = 5.1$), respiratory exchange ratio ($p = 0.001$, $d = 3.3$) and heart rate ($p = 0.001$, $d = 12.3$) values were substantially elevated from baseline. The excess post-exercise $\dot{V}O_2$ ($p = 0.001$, $d = 4.7$), minute ventilation ($p = 0.001$, $d = 3.5$), respiratory frequency ($p = 0.001$, $d = 3.6$), tidal volume ($p = 0.001$, $d = 2.5$) and heart rate ($p = 0.001$, $d = 3.0$) values remained elevated at the post-workout 5 min of recovery compared to baseline, with excess post-exercise $\dot{V}O_2$ ($p = 0.026$, $d = 0.8$) and respiratory exchange ratio ($p = 0.001$, $d = 1.8$) values greater than the exercise condition. In contrast, minute ventilation ($p = 0.001$, $d = 2.5$), respiratory frequency ($p = 0.001$, $d = 3.1$) and heart rate ($p = 0.001$, $d = 3.7$) were higher along the exercise compared with the recovery period. Regarding metabolic variables, there was a 14-fold increase in [La⁻] and a 46% increase in glucose levels in post-exercise values compared to baseline. The perceived exertion was much higher at the 30 min of recovery than at baseline (Table 1).

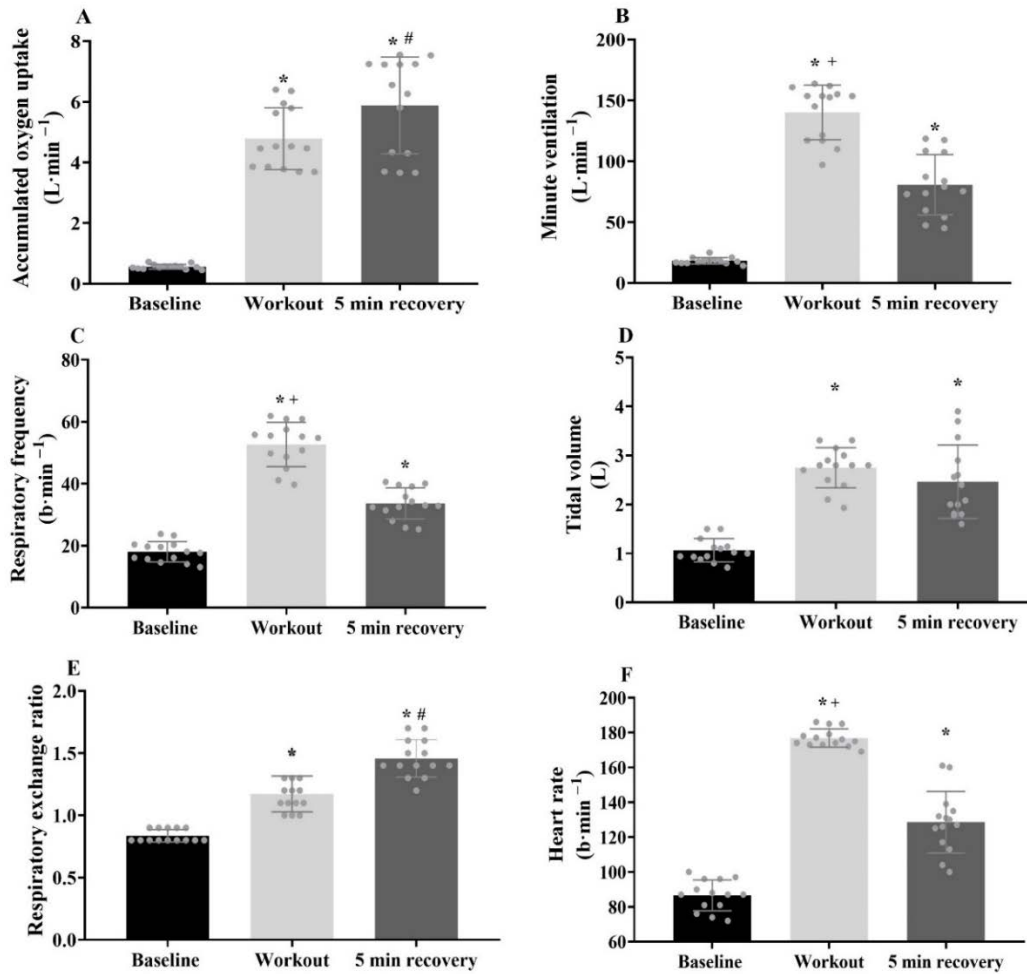


Figure 4. Cardiorespiratory variables assessed during baseline, Isabel workout and recovery with the respective differences identified by *, # and +, respectively ($p \leq 0.05$). Individual and mean $\pm$ SD values.

Table 1. Baseline and Isabel workout metabolic demands and perceived exertion.

Variable	Baseline	Isabel	p	d
Peak blood lactate ($mmol \cdot L^{-1}$)	1.5 ± 0.3	20.7 ± 2.6	.001	9.8
Peak blood glucose ($mg \cdot dL^{-1}$)	97.1 ± 4.6	141.8 ± 8.6	.001	6.2
Rating of perceived exertion (6-20 scale)	6 ± 1	18 ± 2	.001	7.5

Mean $\pm$ SD, probability (p) and effect size (d).

The absolute and relative energy contribution values for the total workout are presented in Figure 5, with the oxidative phosphorylation ($p = 0.001$, $d = 4.0$) and glycolytic pathway ($p = 0.001$, $d = 4.7$) systems values contributing substantially more than the phosphagen pathway system (with higher values for glycolytic pathway contribution than the oxidative phosphorylation system). Total energy expenditure and metabolic power values during the Isabel workout

were 245 ± 25 kJ and 2.0 ± 0.2 kW, and the caloric expenditure was lower during the workout than during the recovery period (101 ± 22 vs. 124 ± 34 kJ; $p = 0.026$, $d = 0.8$).



Figure 5. Isabel workout (absolute and relative) aerobic, anaerobic lactic and anaerobic alactic energy contributions (identified by dark grey, light grey and white). * Differences from anaerobic alactic ($p < .001$).

Discussion

We characterized the $\dot{V}O_2$ kinetics, estimated the energy system contributions and evaluated the total energy expenditure of the Isabel CrossFit® workout. This exercise is typically performed in ~120 s and generates energetic demands in the extreme intensity domain (Hill et al., 2002). Our main findings are summarized as follows: (i) a fast $\dot{V}O_2$ increase occurred at the beginning of the workout and continued to rise during the exercise yielding a high accumulated $\dot{V}O_2$; (ii) a greater contribution of the oxygen-independent metabolism (~60% of the total energy release) was observed (as a sum of both the glycolytic and phosphagen pathways); and (iii) the total energy expenditure values were high. The velocity of muscle contraction during the workout resulted in higher cardiorespiratory and metabolic stress (evidenced by the excess post-exercise $\dot{V}O_2$, $[La^-]$ and glucose values) compared to baseline, which ultimately affected the return to homeostasis. These high metabolic demands confirm the utility of the CrossFit® Isabel workout as a very effective high-intensity training modality for enhancing fitness and conditioning.

It is well established that performing an a priori test in a standardized protocol, such as an intermittent incremental treadmill test, allows the collection of $[La^-]$ analysis and, in conjunction with gas exchange assessments, provides a comprehensive physiological characterization of exercise in the low, moderate, heavy and severe intensity domains (F. Cardoso et al., 2022). However, advocating an a priori standardized testing protocol to determine maximal $\dot{V}O_2$ (e.g., cycling, treadmill and rowing ergometer) and comparing it to the Isabel performance that includes specific strength training elements compromises the principle of modality specificity in sports training. For this reason, we chose not to perform a priori tests to determine the maximal $\dot{V}O_2$ of crossfitters. Instead, we compared their values with cardiorespiratory data from athletes participating in sports performed at the same intensity.

Although $\dot{V}O_2$ kinetics is well described in the literature, especially in cyclic sports (Poole & Jones, 2012; Sousa, Rodríguez, et al., 2015), few attempts have been made in the CrossFit® literature to evaluate $\dot{V}O_2$ kinetics using direct oximetry protocols under real exercise conditions. When the Isabel workout is performed at maximal effort, crossfitters begin exercising at a very high intensity. From the onset of the exercise, the requirement for oxygen in muscles triggers an instantaneous and sudden increase in the accumulated $\dot{V}O_2$, resulting in a high peak $\dot{V}O_2$, which is consistent with recently reported data obtained in trained crossfitters performing the CrossFit® Fran workout (Rios, Becker, et al., 2024; Rios, Zacca, et al., 2023). The current primary component amplitude and time constant values were similar (but with smaller values for the time delay) than those previously reported for rowing, running and cycling at maximal intensity (Sousa, Figueiredo, et al., 2015). Faster $\dot{V}O_2$ kinetics is related to a shorter time lag in the imbalance of $\dot{V}O_2$ demand and supply, implying an increased oxidative contribution to energy transfer (Burnley & Jones, 2007). In addition, given that the crossfitters were trained, it likely influenced a shorter time constant (associated with higher fatigue tolerance) contributing to better performance (Burnley & Jones, 2007; Whipp et al., 2002).

Cardiorespiratory outcomes during the Isabel workout yielded similar values for minute ventilation, respiratory frequency, tidal volume, respiratory exchange ratio and heart rate compared with running and cycling at maximal intensity (F.

Cardoso et al., 2022; Sousa, Figueiredo, et al., 2015). However, the accumulated $\dot{V}O_2$ and heart rate values were lower than those obtained in the previous evaluation of the Fran workout (Rios, Becker, et al., 2024; Rios, Zacca, et al., 2023). The differences in accumulated $\dot{V}O_2$ values can be explained by the greater exercise volume involved in this latter effort (90 repetitions of thrusters plus pull-ups) that ends up demanding a greater pulmonary function (Rios, Becker, et al., 2024; Rios, Zacca, et al., 2023). In support of this assertion, the short duration of the Isabel workout (combined with the extreme intensity) limited the increase in heart rate and prevented it from reaching a higher value (Tibana et al., 2018). The $[La^-]$ and glucose concentrations in response to the extreme intensity of the Isabel workout were higher than the Grace and Fran CrossFit® workouts (Kluszczewicz et al., 2017; Rios, Becker, et al., 2024), reflecting a greater glycolytic pathway contribution and involvement of carbohydrate metabolism. These effects would likely reflect a greater amount of glucose at the muscle level (Gastin, 2001). The perceived exertion was lower in the Cindy (Maté-Muñoz et al., 2018) and Fran (Rios, Zacca, et al., 2023) workout sessions compared to the Isabel workout, which was classified as extremely hard. A higher rating of perceived exertion value during an intense workout session indicates that sufficient stimuli are present to promote resistance adaptation, as the rating of perceived exertion value has been used as a marker of psychophysiological response to a training session (Gomes et al., 2022).

The oxidative phosphorylation contribution determined in the current study was lower than the values previously reported for Fran workout (Rios, Becker, et al., 2024), running, cycling (Sousa, Figueiredo, et al., 2015) and rowing (R. Cardoso et al., 2022), but higher than the values reported for strength training (Vianna et al., 2011). In contrast, the oxygen-independent metabolism (phosphagen and glycolytic pathways) contribution during Isabel workout in the present study was higher than that reported for the other types of training (R. Cardoso et al., 2022; Rios, Zacca, et al., 2023), although these differences could be attributed to the shorter total duration (117 s) and high net $[La^-]$ accumulation ($1.5\text{--}20.7\text{ mmol}\cdot\text{L}^{-1}$) of the Isabel workout (Gasti, 2001). In addition, specific mechanical factors (e.g., the muscle contraction scheme and

the resulting muscle fiber recruitment profile itself) might have influenced the energy contribution of the workout, which in turn largely depends on the type of training performed (Reis et al., 2017). Nevertheless, some caution should be exercised when interpreting data, as different methodological procedures can easily influence the energy contribution (Gastin, 2001). The gold standard for assessing oxygen-independent metabolism release involves a highly invasive muscle biopsy, quantifying energy sources and metabolite accumulation inside muscle cells. However, the technique's limitation lies in sampling only a small portion of human muscle tissue, requiring multiple samples from different depths to reflect muscle heterogeneity (Rios et al., 2022).

Studies that have examined total energy expenditure, metabolic power and caloric expenditure assessment under CrossFit® training conditions, particularly at extreme intensity, are few in number. Total energy expenditure during the Isabel workout was lower than the Cindy and Fran workouts (Kliszczewicz et al., 2017; Rios, Zacca, et al., 2023), but higher than those reported for strength training (Scott et al., 2011) and rowing (R. Cardoso et al., 2022). Metabolic power reported in this study was higher compared to the Fran workout (Rios, Zacca, et al., 2023) and rowing (R. Cardoso et al., 2022), while caloric expenditure was lower compared to strength training (Brewer et al., 2021), Cindy (Kliszczewicz et al., 2017) and Fran workouts (Rios, Becker, et al., 2024; Rios, Zacca, et al., 2023). These differences could be due to intensity, volume, the number of repetitions and different types of exercises (Reis et al., 2017), and provide a framework for the prescription of training in these settings.

Cardiorespiratory function remained elevated during the recovery period (as expected) compared with baseline values, consistent with other exercises (Rios, Becker, et al., 2023; Thornton & Potteiger, 2002). This elevation is justifiable because strength training can induce Valsalva maneuvers and an increase in cardiovascular demands, which may yield a compensatory rise in minute ventilation and $\dot{V}O_2$ during the recovery period (Ratamess et al., 2018; Ratamess et al., 2014). In addition, the higher minute ventilation and $\dot{V}O_2$ could also be interpreted as part of the compensation to normalize the lowered pH caused by increased $[La^-]$ levels post-workout (Ratamess et al., 2018; Thornton & Potteiger, 2002). The higher respiratory exchange ratio during the recovery

compared to baseline and exercise conditions is likely explained by the explosive nature of the Isabel workout. The Isabel requires a rapid production of adenosine triphosphate via the oxygen-independent metabolism (60%), resulting in a greater involvement of carbohydrate metabolism (Gastin, 2001).

Our results indicate that Isabel's workout, completed in less than two min, triggers a substantial and effective cardiorespiratory response. This regimen could serve as an excellent training option for optimizing both oxygen-independent metabolism and oxidative phosphorylation pathways. Certain limitations in our study warrant acknowledgment. First, the relatively small number of participants and the absence of dietary control before the test must be acknowledged. Caution should be used when extrapolating the results of the current study to other cohorts or individuals with different training experiences, as only healthy, experienced, male participants were recruited for this study. Several variables, including active muscle mass percentage, a time constant of $\dot{V}O_2$ on the response at the muscle level and the concentration of phosphocreatine splitting per kilogram of wet muscle, can influence the values obtained using the phosphagen pathway method (Rios et al., 2022). Finally, this study lacks biochemical markers (e.g., creatine kinase, total antioxidant status and malondialdehyde) to elucidate the elevated physiological stress induced by a single training session of Isabel.

In future cross-sectional studies, comparing cardiorespiratory responses and energy utilization between novice and experienced crossfitters is valuable. Furthermore, future research should assess the metabolic profile of novice participants to understand the impact of strategies employed during the Isabel workout in this cohort. It is crucial to explore variations in these responses between males and females, emphasizing adaptations in both central (stroke volume) and peripheral (oxidative capacity) aspects. Longitudinal studies analyzing the effects of prescribed training interventions over weeks in response to the consecutive days of CrossFit® training, using similar methods and including biochemical markers and biomechanics analysis, are crucial for a comprehensive understanding of how to accurately quantify and monitor CrossFit® training load.

Conclusions

During the extremely intense Isabel workout, there was an immediate and sudden increase in $\dot{V}O_2$ at the beginning of the exercise that persisted until the end, highlighting the contribution of oxidative phosphorylation energy metabolism during short and very intense CrossFit® workouts. The majority (~60%) of the total energy was obtained from oxygen-independent metabolism, and both the glycolytic and phosphagen pathway energy systems should be strengthened to improve the performance of trained male crossfitters. The Isabel workout is an excellent high-intensity training option for crossfitters and other athletes seeking to improve their fitness and conditioning.

Chapter 7

Biomechanical Characterization of the CrossFit® Isabel Workout: A Cross-Sectional Study

Manoel Rios,^{1,2} Ricardo Cardoso,^{1,2} Pedro Fonseca,² João Paulo Vilas-Boas,^{1,2} Victor Machado Reis,^{3,4} Daniel Moreira-Gonçalves,^{5,6} and Ricardo J. Fernandes^{1,2}

¹Center of Research, Education, Innovation and Intervention in Sport, Faculty of Sport, University of Porto, Porto, Portugal

² Porto Biomechanics Laboratory, Faculty of Sport, University of Porto, Porto, Portugal

³Department of Sport Sciences, Exercise and Health, University of Trás-os-Montes e Alto Douro, Vila Real, Portugal

⁴Research Center in Sports Sciences, Health Sciences and Human Development, Vila Real, Portugal

⁵Research Center in Physical Activity, Health and Leisure, Faculty of Sport, University of Porto, Portugal

⁶Laboratory for Integrative and Translational Research in Population Health, Porto, Portugal

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Abstract

A cross-sectional study was conducted to biomechanically characterize Isabel's workout (30 snatch repetitions with 61 kg fixed weight), focusing on eventual changes in knee, hip and shoulder angles. A three-dimensional markerless motion capture system was used to collect data from 11 highly trained male crossfitters along the Isabel workout performed at maximal effort. The routine was analyzed globally and in initial, middle and final phases (10, 20 and 30 repetitions, respectively). Lift total time increased (1.51 ± 0.18 vs. 1.97 ± 0.20 s) and maximal lift velocity (2.64 ± 0.12 vs. 2.32 ± 0.13 m/s) and maximal lift power (15.58 ± 2.34 vs. 13.80 ± 2.49 W/kg) decreased from the initial to final phases, while the time from lift until the bar crossed the hip and shoulder (34.20 ± 4.00 vs. 27.50 ± 5.10 and 39.70 ± 16.80 vs. $30.90 \pm 13.90\%$) decreased along the Isabel workout. In addition, a decrease in hip flexion was observed during the last two phases when the bar crosses the knee (62.62 ± 24.80 vs. $53.60 \pm 19.99^\circ$). Data evidence a decrease in the power profile and a change in hip flexion throughout the Isabel workout, without compromising the other joints.

Key words: Biomechanics; CrossFit®; snatch; technique analysis

Introduction

Physical fitness benefits related to high-intensity exertion and a sense of community have led CrossFit® to an unprecedented level of global popularity (Claudino et al., 2018). In fact, the CrossFit® program has quickly become one of the fastest-growing training concepts, boasting over 15,000 affiliated training centers and 5 million athletes worldwide (Meier et al., 2023). CrossFit® workouts involve functional movements executed at high intensity, known as the workout of the day, typically including gymnastics exercises, metabolic conditioning, and Olympic weightlifting (Meier et al., 2023; Rios et al., 2021). These activities are executed in rapid succession, often prioritizing maximal numbers of repetitions within a specific period or completing a designated set of repetitions in the shortest time duration (Rios, Becker, Cardoso, et al., 2024; Tibana & de Sousa, 2018). Like other high-intensity resistive exercise modes, CrossFit® improves body composition, muscle strength and cardiorespiratory fitness (Claudino et al., 2018). To assess these changes in fitness levels and monitor work capacity, CrossFit® uses benchmark workouts, like Cindy (Forte et al., 2022; Maté-Muñoz et al., 2017) and Fran (Rios, Becker, Monteiro, et al., 2024; Rios et al., 2023) that are among the most extensively studied (Meier et al., 2023). The benchmark workouts are standardized, meaning athletes use the prescribed weight or height, complete the specified number of repetitions, and follow the exact movement patterns, to ensure performance comparability with athletes worldwide, regardless of location or environment (Meier et al., 2023; Peña et al., 2021; Rios et al., 2023). However, mounting evidence indicates that certain CrossFit® workouts, paired with insufficient recovery periods, may heighten the risk of overload, fatigue and injury, especially in poorly trained individuals (Claudino et al., 2018; Tibana & de Sousa, 2018).

The incidence of injuries in CrossFit® spans strength-related sports from 0.2–18.9/1000 h of participation, mirroring rates observed in other sports like weightlifting and powerlifting (Feito et al., 2018; Klimek et al., 2018). In fact, the predetermined external loads and repetition volumes set for CrossFit® routines can exert a significant influence on the kinematics and kinetics of movements, with the imposition of significant loads on the knee, hip and shoulders amplifying the susceptibility to injuries (Klimek et al., 2018; Tibana & de Sousa,

2018). Potential contributor to CrossFit-related injuries, particularly shoulder injuries, is muscular fatigue from the high number of repetitions performed during sessions (Hak et al., 2022). For example, the CrossFit® Isabel workout requires completing 30 power snatch repetitions within a 2 min period (with a predominance of the anaerobic component), with a constant external load of 61 kg (Peña et al., 2021; Rios, Becker, Cardoso, et al., 2024). This emphasis on anaerobic exertion, coupled with fatigue accumulation throughout the routine (due to the accumulation of hydrogen ions reducing pH and causing metabolic acidosis, as well as the inhibition of phosphofructokinase) (Smilios et al., 2010), may compromise movement biomechanics, increasing injury risk for crossfitters (Claudino et al., 2018; Tibana & de Sousa, 2018). The relationship between fatigue and movements, especially prevalent in CrossFit® workouts that feature technically demanding weightlifting exercises and heavy loads, necessitates attention (Klimek et al., 2018; Ribeiro et al., 2024; Tibana & de Sousa, 2018).

The power snatch, by lifting the bar from the floor to a position above the head with the upper limbs fully extended in one continuous movement (Nagao et al., 2023; Stone et al., 1998), is a commonly incorporated exercise in strength and power training within CrossFit® programs (Claudino et al., 2018; Rios, Becker, Cardoso, et al., 2024). It stands out as the most technical component of weightlifting in CrossFit® competitions, demanding a precise mechanical execution (Nagao et al., 2023; Stone et al., 1998). In weightlifting, success in the snatch is contingent upon the load lifted and is achieved through optimal force generation by maintaining specific positions during precise phases that align with an individual's optimal biomechanics (Chavda et al., 2021). Numerous kinetic and kinematic variables related to both the barbell have been documented to elucidate the snatch and its individual components, including power, velocity and barbell displacement (Harbili & Alptekin, 2014; Nagao et al., 2023). Previous studies indicate that as the load increases, the pull duration rises, while the maximal and mean velocities, as well as the power output, decrease (Garhammer, 1993; Harbili & Alptekin, 2014). In addition, it has been reported that the snatch initial phase is slower and emphasizes force, while the second phase is faster and leans towards power (Garhammer, 1993; Harbili & Alptekin, 2014).

Despite the increase in scientific studies due to the growing popularity of CrossFit®, there remains significant room for future research on the biomechanical analysis CrossFit® benchmark workouts (e.g., Isabel). In fact, while many studies have evaluated the biomechanics of the snatch (Gourgoulis et al., 2009; Harbili & Alptekin, 2014; Nagao et al., 2023), research on its use with high volume (e.g., 30 repetitions) and constant load (e.g., 61 kg) is limited. Really, the Isabel workout may alter snatch kinematics, potentially increasing joint load and injury susceptibility (Klimek et al., 2018; Tibana & de Sousa, 2018). Hence, given the cumulative overload volume on crossfitters, it is crucial to characterize this workout along its full duration.

The purpose of the current study was to analyze from a biomechanical point of view the CrossFit® Isabel workout performed at maximal intensity, focusing on changes in knee, hip and shoulder angles. We hypothesized that velocity and power values would be elevated in the initial segment of the routine, followed by a gradual decrease in subsequent repetitions, accompanied by a reduction in knee and hip angles throughout the workout.

Materials and methods

Participants

Eleven highly trained male crossfitters, aged 28.4 ± 6.0 years, with an average height of 176.8 ± 10.3 cm, body mass of 87.7 ± 11.8 kg, lean mass of $44.4 \pm 7.5\%$, fat mass of $11.2 \pm 4.2\%$, body mass index of 28.0 ± 2.4 kg/m² and 5.6 ± 1.6 years of CrossFit® training experience, volunteered for the current study. Participants were recruited through detailed announcements at local CrossFit® affiliate gyms based on the following criteria: (i) training CrossFit® at least five times a week for a minimum of three years and having prior experience in national and international competitions; (ii) the ability to complete the Isabel workout in under 2 min; (iii) age between 20 and 30 years and clearance according to the Physical Activity Readiness Questionnaire; (iv) being free of injuries and known illnesses; and (v) not using performance-enhancing drugs. Male who did not meet the inclusion criteria were excluded, as were those with cardiovascular, pulmonary or neuromuscular conditions that could affect the

results. Participants were instructed to maintain their usual nutritional habits, abstain from alcohol and caffeine consumption, and avoid intense physical activity 48 h before the test. Detailed information about the experimental procedures, associated risks and benefits of participation were provided. All volunteers read and signed an informed consent form in accordance with the Declaration of Helsinki and guidelines of the World Medical Association for research involving humans, with the study being approved by the local Ethics Committee (CEFADE212019).

Experimental Design

Following a cross-sectional design, each experienced crossfitter underwent an evaluation under consistent environmental conditions (20 °C ambient temperature, 60% humidity and between 8 a.m. to noon [12 p.m.]). All tests were conducted in the same laboratory facilities and supervised by experienced researcher. Each participant underwent a series of descriptive measurements to evaluate body composition and anthropometrics. Body mass and height were taken before the experimental session using a bioimpedance scale (InBody 120, Biospace, Seoul, Republic of Korea) and a stadiometer (model 220, SECA, Hamburg, Germany), and body mass index calculated by dividing body mass by height squared. Each crossfitter was assessed using the standard methods established by the International Society for the Advancement of Kinanthropometry (Marfell-Jones et al., 2006). After a 10 min warm-up period for joint mobility and Isabel specific exercise with low loads (10 repetitions at 40% of Isabel's training weight), each participant performed the Isabel workout at maximal exertion. An expert researcher supervised each repetition of the snatch to ensure proper execution of the movements. Kinematic and kinetic variables were measured continuously and performance timing was quantified using a Seiko stopwatch (Yokohama, Japan). The effort was analyzed globally and divided in its initial, middle and final phases corresponding to 10, 20 and 30 repetitions, respectively).

Isabel Workout

The Isabel is a CrossFit® benchmark workout consisting of completing 30 power snatches for time, using a prescribed weight of 61 kg for male and 43 kg for female. The objective is to perform the snatches as quickly as possible, maintaining proper form and technique throughout the workout (Peña et al., 2021; Rios, Becker, Cardoso, et al., 2024). The Isabel workout was chosen because it consists of only one exercise and requires a high number of repetitions performed as quickly as possible. In addition, the snatch is a very popular and commonly practiced exercise in CrossFit® routines. To qualify for participation in the present study, crossfitters had to complete the workout in 2 min or less, as this time frame classifies them as elite crossfitters (Rios, Becker, Cardoso, et al., 2024).

Methodology

The participants kinematic data were recorded using eight Miquis video cameras (Qualisys AB, Göteborg, Sweden), operating at 100 Hz and 720 p resolution, with a maximum calibration error of 0.50 mm (Cardoso et al., 2024). Full-body markerless kinematics with 6° of freedom were obtained by post-processing the video recordings using the Theia Markless (2023.1.0.3161_ P14, Kingston, ON, Canada) software. In addition, the bar displacement was obtained by placing a 12.0 mm retroreflective marker in each extremity and recording its position using a 12 cameras infrared motion capture system (Miquis, Qualisys AB, Göteborg, Sweden), operating at 100 Hz and in synchrony with the markerless video cameras. The markerless and marker-based kinematics were merged in Visual3D (HAS-Motion, Kingston, ON, Canada), where further processing and analysis of the data was performed (Cardoso et al., 2024). The bar lift total time, maximal and average power and velocity were obtained from the start to the end of the lift movement. The movement initiation was considered as the first instant that the bar velocity crosses the 0.2 m/s threshold in the upward direction, while the end lifting was considered at the maximum height of the bar. The angles of the knee, hip and shoulder joints were recorded when the bar crossed these anatomical shoulder positions (Figure 1). All angles were calculated as the angle of the distal segment in relation to the proximal

segment. All kinematic data was filtered with a 6 Hz bidirectional low-pass Butterworth filter in Visual3D software (v2024.03.3).

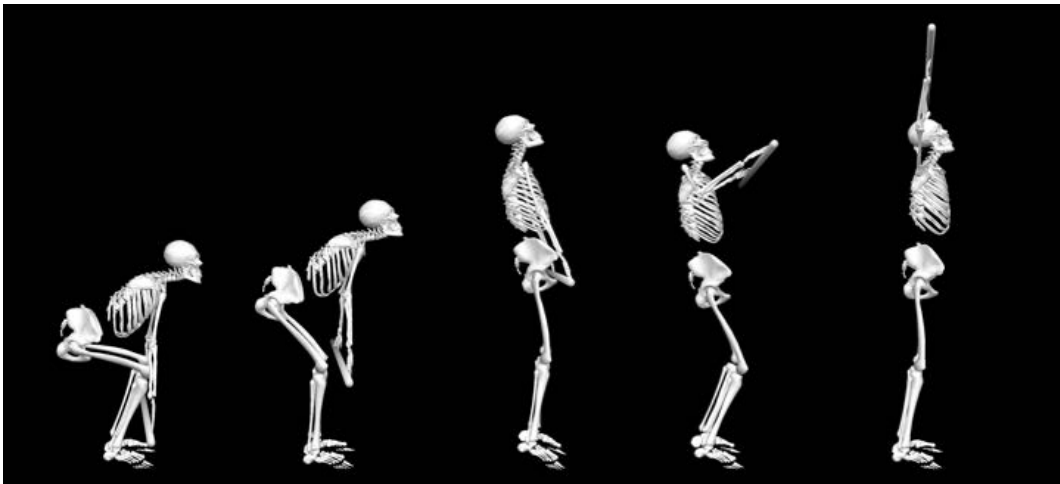


Figure 1. Individual kinematic example of the sagittal plane at the initial phase, bar crossing the knee, hip and shoulder, and final position (from left to right, respectively).

Statistical Analysis

All statistical calculations were completed using GraphPad Prism 6, with mean and standard deviation (SD) values for descriptive analysis reported for all variables. The Shapiro-Wilk test was used to assess data normality and repeated-measures analysis of variance (with a Bonferroni correction) was used to compare the performances during in the start, middle and final phases of each experimental condition. Based on a priori power analysis, a sample size of 19 subjects, a large effect size (0.138) and a 0.05 overall level of significance, the statistical power was 0.80 (G*Power 3.1.9.7, Heinrich-Heine-Universität Düsseldorf, Germany). However, adhering to the inclusion criteria (e.g., participating in national and/or international competitions, and the ability to complete the Isabel workout in under 2 min), only 11 crossfitters were available for analysis, reducing the statistical power to 0.58. Effect sizes were determined using Cohen's *d* and interpreted as trivial (<0.2), small (0.2–0.6), moderate (0.6–1.2), large (1.2–2.0) and very large (>2.0). Statistical significance was set at $p < 0.05$.

Results

The Isabel workout performance and biomechanical variables are reported in Table 1. The overall Isabel workout duration was 116 ± 11 s, with lift total time (initial vs. middle, $p = 0.003$, $d = 0.9$; initial vs. final, $p = 0.001$, $d = 2.4$; middle vs. final, $p = 0.001$, $d = 1.1$) increased. The maximal lift velocity (initial vs. middle, $p = 0.001$, $d = 1.2$; initial vs. final, $p = 0.001$, $d = 2.5$; middle vs. final, $p = 0.007$, $d = 1.1$) and maximal lift power (initial vs. middle, $p = 0.015$, $d = 0.3$; initial vs. final, $p = 0.004$, $d = 0.6$; middle vs. final, $p = 0.046$, $d = 0.3$) decreasing from the first to the last phase. The time to average lift velocity (initial vs. middle, $p = 0.001$, $d = 1.3$; initial vs. final, $p = 0.001$, $d = 2.4$) and average lift power (initial vs. middle, $p = 0.002$, $d = 0.4$; initial vs. final, $p = 0.007$, $d = 1.0$) decreased until the final phase (remaining constant in the last two phases). The time from the lift until the bar crossing the hip (initial vs. middle, $p = 0.001$, $d = 1.1$; initial vs. final, $p = 0.002$, $d = 1.2$) and shoulder phases (initial vs. middle, $p = 0.006$, $d = 0.2$; initial vs. final, $p = 0.019$, $d = 0.6$) decreased progressively along the routine, with the smallest values observed at the final phase (see Table 1). A decrease in hip flexion was observed during the last two phases when the bar crosses the knee (initial vs. middle, $p = 0.006$, $d = 0.2$; initial vs. final, $p = 0.019$, $d = 0.6$). In contrast, an increase in knee extension was observed as the bar crosses the shoulder (initial vs. middle, $p = 0.039$, $d = 0.4$; initial vs. final, $p = 0.039$, $d = 0.8$).

Table 1. Mean and SD values of the studied variables for the different phases and overall execution of the Isabel workout.

Variables	Initial phase	Middle phase	Final phase	Overall
Lift total time (s)	1.51 ± 0.18	1.71 ± 0.27*	1.97 ± 0.20* #	1.77 ± 0.25
Maximal lift velocity (m/s)	2.64 ± 0.12	2.48 ± 0.15*	2.32 ± 0.13* #	2.48 ± 0.12
Average lift velocity (m/s)	1.19 ± 0.14	1.08 ± 0.14*	0.98 ± 0.11* #	1.08 ± 0.12
Maximal lift power (W)	1425.24 ± 267.17	1503.33 ± 275.95*	1259.99 ± 248.85* #	1338.81 ± 255.60
Maximal lift power (W/kg)	15.58 ± 2.94	14.75 ± 2.59*	13.80 ± 2.49* #	39.00 ± 8.70
Average lift power (W)	636.80 ± 149.94	567.75 ± 159.99*	493.30 ± 134.57*	567.26 ± 141.32
Average lift power (W/kg)	6.94 ± 1.41	6.15 ± 1.56*	5.41 ± 1.53*	5.73 ± 1.42
Time to knee cross (% lift total time)	18.10 ± 2.10	11.70 ± 6.90	10.90 ± 6.80	15.60 ± 2.00
Time to hip cross (% lift total time)	34.20 ± 4.00	29.30 ± 4.50*	27.50 ± 5.10*	30.00 ± 3.00
Time to shoulder cross (% lift total time)	39.70 ± 16.80	35.50 ± 15.80*	30.90 ± 13.90*	39.00 ± 8.70
Time to maximal lift velocity (% lift total time)	39.20 ± 4.10	33.20 ± 5.30*	29.40 ± 4.00*	33.80 ± 3.70
Knee angle at knee cross (°)	37.49 ± 14.54	34.44 ± 9.44	29.04 ± 3.49	33.66 ± 8.90
Knee angle at hip cross (°)	40.66 ± 18.80	41.65 ± 16.02	36.79 ± 9.77	19.25 ± 11.07
Knee angle at shoulder cross (°)	35.18 ± 9.40	39.34 ± 9.30*	42.86 ± 9.23*	36.41 ± 13.51
Hip angle at knee cross (°)	62.62 ± 24.80	58.33 ± 23.36*	53.60 ± 19.99*	58.18 ± 22.63
Hip angle at hip cross (°)	20.29 ± 11.63	18.38 ± 10.82	19.07 ± 5.98	39.70 ± 14.33
Hip angle at shoulder cross (°)	9.21 ± 6.94	9.45 ± 7.43	9.80 ± 6.33	9.49 ± 6.74
Shoulder angle at knee cross (°)	42.26 ± 4.45	41.02 ± 4.15	40.35 ± 3.10	41.21 ± 3.75
Shoulder angle at hip cross (°)	48.56 ± 5.28	48.15 ± 5.29	47.12 ± 5.98	47.94 ± 5.20
Shoulder angle at shoulder cross (°)	68.74 ± 11.37	69.68 ± 10.22	69.33 ± 10.42	69.25 ± 10.56

*and # correspond to differences the relative to initial and middle phases, respectively (p < 0.05).

Figure 2 illustrates the Isabel power snatch movement, detailing the overall lift and its three phases, as well as the time taken for the bar to cross the knee, hip, shoulder, and reach the final position.

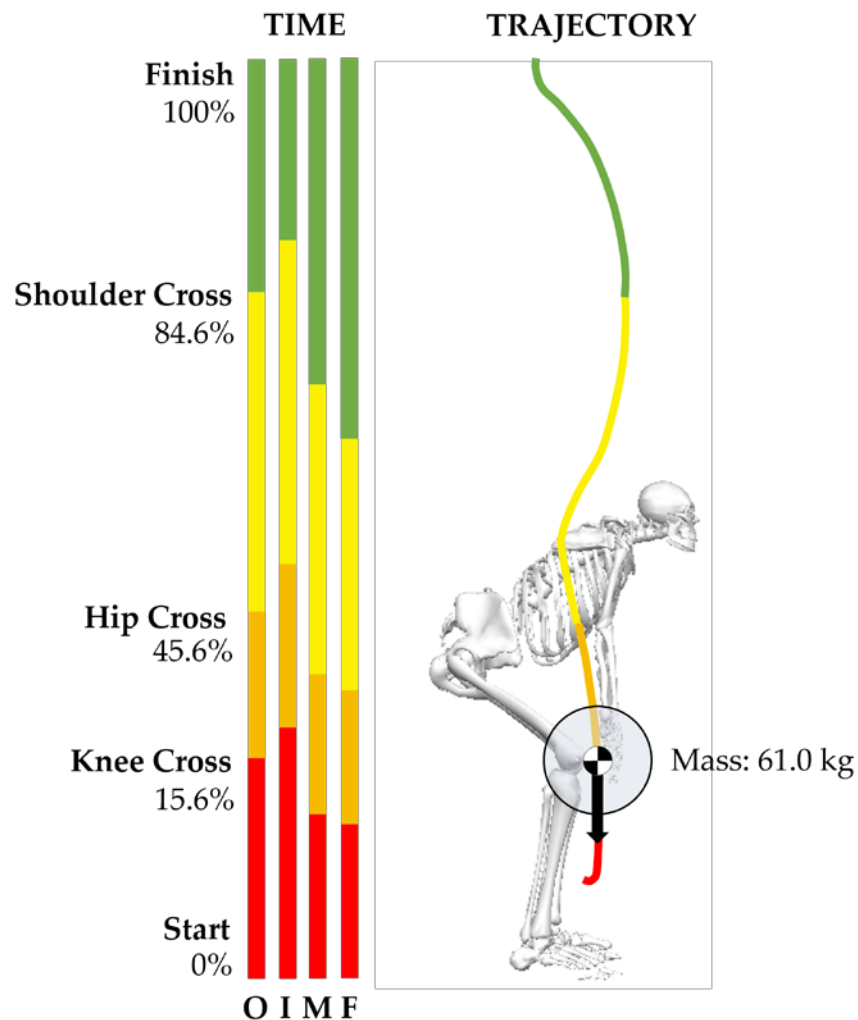


Figure 2. Representation of the lift trajectory and time until it the bar crosses the knee (red), hip (orange), shoulder (yellow) and achieves the finish position (green). The chromatic range depicts the distribution of these phases during the overall exercise (O), initial phase (I), middle phase (M) and final phase (F).

Discussion

We assessed the biomechanics characteristics of the Isabel CrossFit® workout, which is typically performed in ~120 s and elicits very significant energy demands (Rios, Becker, Cardoso, et al., 2024). Our mains findings were that: (i) an increase in total lift time, and decrease maximal lift velocity and maximal lift power occurred in the middle phase and continued to decrease throughout the elevation; (ii) average lift power decreased until the workout final phase,

remaining constant in the last two phases; (iii) there was a gradual decrease in the time from lift until the bar crossed the hip and shoulder throughout the routine, with the lowest values being observed in the final phase; and (iv) as the number of repetitions succeed, a trend toward a decreased hip flexion was observed during the last two phases when the bar crossed the knee, while an increase in knee extension was noted when the bar cross the shoulder. Collectively, these outcomes indicate that the high demands of Isabel workout impact the power profile of crossfitters, while also affecting changes in hip flexion throughout the specific workout without compromising the other joints.

While the biomechanics of the snatch during single repetition efforts are well documented in the literature, particularly in weightlifting and powerlifting (Harbili & Alptekin, 2014; Nagao et al., 2023), research in the context of CrossFit® is scarce, especially using benchmark workouts under real exercise conditions. In the current study, the substantial volume of repetitions with a constant load impacted the total lift time, velocity and maximal power production throughout the workout. This decline was expected and aligns with the increased metabolic demands and muscle fatigue associated with extreme-intensity exercise over time (Peña et al., 2021; Rios, Becker, Cardoso, et al., 2024). Moreover, the decrease in the average lift power until the workout final phase, while remaining constant in the last two phases, suggests a potential adaptation of performance despite the continued effort. This adjustment in pacing likely reflects an attempt to maintain consistent performance levels despite increasing fatigue, slowing the velocity of muscle contraction (Nagatani et al., 2023; Tufano et al., 2016).

The time from lift until the bar crosses over the knee, hip and shoulder progressively increased throughout the Isabel routine, correlating with the increase in time to reach maximal lift velocity. These results are supported by findings that elite weightlifters experience a decline in barbell velocity, potentially due to excessively rapid initial movement or fatigue (Gourgoulis et al., 2000; Harbili & Alptekin, 2014). Previous research has demonstrated that the Isabel workout performed in ~2 min exhibits a greater anaerobic predominance, reflecting the increased recruitment of type II muscle fibers, which are more susceptible to fatigue (Rios, Becker, Cardoso, et al., 2024). Furthermore, increases in external load during multi-joint exercises can result in

greater task demands on skeletal muscle function (Nagatani et al., 2023; Stone et al., 2006). Even if we did not observed a rise in external load (e.g., 70–90% of one repetition maximum), there was an increase in the total volume of repetitions, influencing the time instant the bar crosses the joints (Kipp et al., 2011).

The observed decrease in hip flexion during the last two phases of the Isabel workout, as the bar crosses the knee, aligns with studies on biomechanics of weightlifting (Harbili & Alptekin, 2014). When the crossfitter takes the bar off the floor, the knee angle tends to increase towards maximum extension (Gourgoulis et al., 2000; Nagao et al., 2023) and the lifter actively pushes the knees towards the bar, facilitating the transition into the pull point (Gourgoulis et al., 2009; Harbili & Alptekin, 2014). This pattern often relates with a decrease in hip flexion as the numbers of repetitions increase, reflecting the dynamic adjustments in movement mechanics throughout the workout (Chen, 2000). This suggests that during the period between lifting and crossing the bar at the hip, the lower limbs may be participating less in generating force, increasing the demand on the trunk extensor muscles to complete the required numbers of repetitions (Chen, 2000). In fact, no angular differences were observed when the bar cross the shoulder point, indicating that the inertia of the bar has already been overcome (Harbili & Alptekin, 2014). This further suggests that the primary cause of angular changes can be attributed to a potential lower limbs fatigue, resulting in a reduction of the lift velocity and the associated power decrease observed in the last two phases of the routine.

In the absence of a dedicated study on power snatch performed with fixed load and numbers of repetitions completed within <2 min, the current study serves as a valuable point of reference, providing a degree of reliability to substantiate the present study observations and inferences. A number of limitations in our study warrant acknowledgment, particularly regarding the relatively small number of participants. It is important to note that despite the recruitment of experienced crossfitters, the fixed load of 61 kg for the Isabel workout, combined with the requirement to complete 30 power snatches ~2 min, presented a significant challenge. Despite these challenges, we believe the findings offer valuable insights, though we agree that increasing the sample size

in future studies would enhance the generalizability and robustness of the results. Therefore, caution should be exercised when extrapolating the results of the current study to other cohorts or individuals with varying training experiences, as only healthy, experienced and male participants were recruited for this study. In future cross-sectional studies, comparing power snatch responses between novice and experienced crossfitters would provide valuable insights. Further studies should include electromyography assessment and other joint angles for an in-depth characterization of Isabel workout.

Conclusions

The current study provides valuable insights regarding the biomechanics of the Isabel CrossFit® workout, shedding light on the performance profiles and adaptations of crossfitters during this extreme intensity workout. Findings evidence significant changes in total bar lift time, velocity and power production throughout the workout, highlighting the impact of intensity workout on power profiles. Despite the decline in biomechanical variables, such as hip flexion, crossfitters demonstrated adaptive pacing strategies to maintain performance levels amid increasing fatigue. Practically, this suggests that athletes should focus on pacing strategies to manage fatigue and maintain performance throughout the workout. In addition, incorporating targeted conditioning to enhance lower limb endurance may mitigate declines in hip flexion and improve overall lift efficiency. Future training programs should consider these biomechanical changes to optimize performance and reduce fatigue-related impacts.

Chapter 8 General discussion

Training control and evaluation are frequently integrated into elite training programs to objectively assess the expected fitness and performance outcomes of crossfitters (Tibana et al., 2019; Poderoso et al., 2019). Although physiological and biomechanical are typically focal points in assessing training and performance, particularly in cyclical sports (Sousa, Figueiredo et al., 2015; Zamparo et al., 2023), research analyzing CrossFit® workouts conducted in a real-world training context are scarce. Considering that the current thesis focused on assessing and characterizing the physiological and biomechanical aspects of CrossFit® Fran and Isabel benchmark workouts, our aims were to: (i) physiologically analyze Fran (one of the most widely used benchmarks for assessing the performance of crossfitters), performed intermittently and unbroken; (ii) assess the level of fatigue induced by this workout and the recovery time course; (iii) compare the cardiorespiratory, hemodynamic and metabolic responses between sexes, to gain insights into the contrasting acute adaptations to Fran workout; (iv) analyze cardiorespiratory function and energetic variables in the Isabel workout performed at extreme intensity domain; (v) evaluate biomechanical variables of the Isabel workout, focusing on changes in knee, hip and shoulder movements; and (vi) conduct all experimental CrossFit® procedures in ecological conditions.

Within the first stage of the project development, our research focused on quantifying the physiological demands of each round of the Fran workout. In addition, we evaluated post-workout fatigue levels and investigated whether this short-duration, high-intensity workout leads to a significant reduction in muscle functionality. The results, compiled in **Chapter 2**, indicate that the three rounds comprising the Fran workout yield high cardiorespiratory demands and engage both energy systems, with a predominance of the anaerobic component, accounting for approximately 59% of overall performance. Furthermore, the increase in blood lactate ($[La^-]$), glucose level ($[Glu]$) and mean and peak HR during and after the Fran workout, as well as the elevated rating of perceived exertion (RPE) values, indicates a severe intensity exercise level when performing this routine (as observed later in **Chapter 3**).

A decrease in exercise frequency was observed in the third round of the Fran workout, reflecting a reduction in muscle function. This decline is associated with the cumulative volume of repetitions of the two exercises at a constant load, leading to heightened metabolic acidosis, as evidenced by the elevation in $[La^-]$ and $[Glu]$ throughout and following the workout (Smilios et al., 2010). The fluctuations in accumulated and peak $\dot{V}O_2$ observed from round to round may be attributed to the shortened exercise duration and the 30 s rest intervals between rounds, facilitating the gradual replenishment of phosphocreatine stores (Gastin, 2001; Rogatzki et al., 2014). In addition, during intense resistance exercise, peripheral arterial vessels in the working muscles may experience compression, potentially impairing muscle perfusion and gas exchange (Buitrago et al., 2013).

The estimated energy contributions align with findings from previous studies involving efforts lasting approximately 40-200 s (Gastin, 2001). As O_2 availability reduces during exercise, the reliance on anaerobic metabolism to sustain muscle contraction increases (Gastin, 2001; Sousa, Figueiredo et al., 2015). Supporting this notion, the elevated anaerobic lactic contribution may be attributed to accumulation of $[La^-]$ throughout the routine (as demonstrated in **Chapters 3 and 5**). This sequence of events leads to heightened recruitment of type II muscle fibers required to complete the workout (Sousa, Figueiredo et al., 2015; Sousa Neto et al., 2022). In contrast, following a period of intense exercise interspersed with short-duration intervals, phosphocreatine concentrations remain depleted, potentially limiting restoration at the onset of subsequent rounds and thus reducing the contribution of the alactic anaerobic energy system (Harris et al., 1977; Rodrigues-Krause et al., 2020).

During 5 min of recovery period, the magnitude of excessive post-exercise oxygen (EPOC) was related to the intensity of the workout and the velocity of muscle contraction throughout the rounds, leading to increased metabolic stress as evidenced by elevated $[La^-]$ and $[Glu]$ levels (similar to **Chapters 3 and 5**). The 24 h post-workout muscle functionality did not return to baseline, indicating incomplete recovery among the crossfitters (as demonstrated herein - **Chapter 3**). Maximal exertion exercise can prolong the recovery time of muscle type II fibers (Harris et al., 1977; Sousa Neto et al., 2022). In addition, since core

muscles play a crucial role in transferring forces to the extremities, the 90 repetitions of thrusts plus pull-ups likely induced fatigue in this muscle group, negatively impacting core stability and activation essential for high plank test scores (Shinkle et al., 2012; Timón et al., 2019).

The second experimental study described in **Chapter 3** addressed the limitations identified in **Chapter 2**, and analyzed the $\dot{V}O_2$ kinetics, characterized the energy systems contributions and the degree of post-workout fatigue of the unbroken Fran workout. We observed that the Fran workout yielded a greater primary amplitude of $\dot{V}O_2$ kinetics, consistent with previous findings in other high-intensity exercise modalities (Carter et al., 2002; Sousa, Rodríguez et al., 2015). Furthermore, there was a marked increase in the contribution of the anaerobic lactic system during the Fran workout. However, the aerobic energy system still accounted for approximately 62% of the total energy demand during the workout. In addition, our data revealed that a single Fran workout led to significant fatigue, which persisted even 24 h after completing the challenge.

An instantaneous and sudden increase in $\dot{V}O_2$ from the beginning of the workout was observed that continued to during the exercise. The $\dot{V}O_2$ mean amplitude was similar to the values observed for severe intensity exercises where maximal $\dot{V}O_2$ is commonly attained (Sousa, Figueiredo et al., 2015; Kramer et al., 2018). In addition, we have reported larger time constant values than those detailed in cycling, swimming and rowing at the same intensity domain (Pringle et al., 2003; Sousa, Figueiredo et al., 2015). The difference observed in this study can likely be explained by the muscle mass and type involved in each exercise modality (Koga et al., 1996; Sousa, Figueiredo et al., 2015). In fact, the unbroken Fran workout entails high levels of muscular tension, which may result in vessel occlusion and hinder blood flow O_2 delivery, thereby delaying the $\dot{V}O_2$ response.

The observed accumulated and peak $\dot{V}O_2$ values were higher when Fran workout was performed unbroken (comparing to the methodology used in **Chapter 2**), and are similar to those obtained for cycling and running (Pringle et al., 2003; Kramer et al., 2018). The difference observed in this study can be explained by the fact that unbroken Fran workout was performed with maximum

effort (without breaks), which allowed for an increase in both accumulated and peak $\dot{V}O_2$ values. In addition, previous studies conducting a standard (Butcher et al., 2015; Dexheimer et al., 2019) maximal and/or peak $\dot{V}O_2$ assessments using treadmill running in experienced crossfitters reported values ranging from 48.6 to 54.7 mL·kg⁻¹·min⁻¹, which is near the range of values reported here for unbroken Fran workout. These outcomes are evidence that appropriate O₂ supply and utilization should not be neglected even in short duration CrossFit® efforts.

The energy contribution values (kJ and %) support our anticipated outcome, indicating a greater contribution from the aerobic system to adenosine triphosphate resynthesis during the unbroken Fran workout. In addition, we observed a significant contribution from the anaerobic lactic system and a lesser involvement of the alactic anaerobic system. Our results indicate that the aerobic contribution is higher during the unbroken Fran workout executed at maximal effort compared to intermittent Fran workout. Moreover, the predominance of anaerobic energy (alactic plus lactic) is higher when Fran workout is performed with intervals (**Chapter 2**). It is possible that the 30 s intervals between the rounds in the intermittent Fran workout influenced the restoration of O₂ stores and phosphocreatine resynthesis, increasing the anaerobic contribution (Tabata et al., 1997). Based on **Chapters 3** and **4**, the unbroken Fran workout can be strategically used to stimulate adaptations in the aerobic pathway, while intermittent Fran workout is effective in promoting adaptations in the anaerobic pathway (Tabata et al., 1997; Gastin, 2001).

The bioenergetic characterization, as an important goal of this thesis, implied the assessment of the controversial anaerobic alactic contribution. Accordingly, in **Chapter 4** was conducted a study to estimate the anaerobic alactic system in the Fran workout through two different methods: (i) using the $\dot{V}O_2$ off-kinetics fast component (Ana_{recovery}) and (ii) estimating the maximal phosphocreatine splitting in the contracting muscle (Ana_{PCr}). We concluded that despite some caveats in both estimations of the anaerobic alactic contribution, both methods yielded similar results and enabled trustworthy estimates of this contribution in the Fran workout performed at maximal effort. Although each method had been studied before (Capelli et al., 1998; Zamparo et al., 2000; Sousa et al., 2013),

this study was the first study to compare them directly, highlighting the importance of the anaerobic alactic contribution, at least for CrossFit® workouts. Therefore, although this study did not identify differences between methods, we selected the Ana_{PCr} method as the standardized criterion to assess the anaerobic alactic system.

The Ana_{recovery} method yielded lower values than those reported for running (Roberts et al., 1978), cycling (Beneke et al., 2002) and boxing (Davis et al., 2014), but similar to swimming (Sousa et al., 2013) and kayaking (Li et al., 2018). These variations were attributed to differences in exercise duration, intensity and activation patterns of muscle masses. The early explanation of the dynamics of recovery $\dot{V}O_2$ was termed alactic (without lactate build-up) and alactic oxygen debt (Margaria et al., 1933). The authors formulated these two explanations after observing that the initial phase of recovery $\dot{V}O_2$ ended before $[La^-]$ began to decline. However, the idea that the $\dot{V}O_2$ fast component during the recovery period is independent of lactic acid removal from the blood has been questioned. In fact, the term oxygen debt received some critical appraisal and another contemporary concept was proposed (excess post-exercise $\dot{V}O_2$), which included the much more prolonged increase in aerobic power observed during post-exercise (Gaesser & Brooks, 1983).

The values of Ana_{PCr} reported in this study are comparable to those described for swimming, rowing and cycling events (Sousa et al., 2013; Sousa, Figueiredo et al., 2015). The Ana_{PCr} method assumes that the energy derived from full utilization of PCr stores (during all-out efforts), which can be estimated assuming during the transition from rest to exhaustion, decreases in concentration relative to the active muscle mass (Zamparo et al., 2011; Sousa et al., 2013). Thus, there are variables that can change the values obtained by the Ana_{PCr} method, such as the percentage of active muscle mass, the associated time constant of $\dot{V}O_2$ on-response at the muscle level, and the concentration of PCr per kilogram of wet muscle (Zamparo et al., 2011).

The gold standard method to assess alactic and lactic anaerobic energy release would require a muscle biopsy, thereby allowing quantification of the energy sources inside the muscle cell (e.g. high-energy phosphates and glycogen) as

well as an accurate measure of metabolite accumulation in the muscle (i.e. muscle lactate) (Reis et al., 2011). A limitation of this technique is that only a limited (minor) portion of the human muscle tissue may be submitted to a biopsy. Moreover, it may be necessary to obtain several samples of tissue located at different depths to attain a sample that is representative of the muscle (Gollnick, et al., 1972) and mirrors the muscle heterogeneity in terms of fiber types (Sjostrom & Friden, 1984). However, the possibility of determining the anaerobic alactic contribution is necessary to adequately assess the total energy expenditure and to relate it to high-intensity CrossFit® workout performance. In addition, CrossFit® researchers, coaches and practitioners should better understand its metabolic demands if they wish to prescribe accurate energetic training goals with the aim of specific workout adaptations.

To complement the findings observed in **Chapters 2, 3 and 4**, and further explore the physiological aspects (e.g. hemodynamic function) to the Fran workout, we compared these responses between sexes to gain insights into the contrasting acute adaptations to exercise (**Chapter 5**). Although most of the factors studied exhibited a similar profile (in terms of hemodynamic and metabolic functions), a notable difference was observed in the total duration of the Fran workout (177 vs 206 s for males and females, respectively). In addition, the faster execution by the male was reflected in higher peak $\dot{V}O_2$ and HR values compared to the female. In fact, females generally demonstrate relatively lower maximal $\dot{V}O_2$ values than males when cycling or running (Leipers et al., 2019). This difference has often been attributed to central factors, such as the presence of a smaller heart and lower hemoglobin mass in females, which can limit their capacity to effectively deliver oxygen to skeletal muscles (Howden et al., 2015). Considering the absence of differences in hemodynamic and metabolic function between the sexes, it appears the variation in physiological response between males and females during an acute Fran workout is influenced by peripheral adaptations.

In addition, considering the responses of cardiorespiratory, bioenergetic and hemodynamic parameters in both intermittent (**Chapter 2**) and unbroken (**Chapter 3**) Fran performance training, alongside the comparative analysis between sexes (**Chapter 5**), confirms its efficacy in improving physical fitness

when contrasted with more moderate exercise intensities (Garber et al., 2011). However, it is important to note the observed increase in metabolic responses and perceived exertion (showed in **Chapters 2, 3 and 5**), accompanied by a decrease in performance on the countermovement jump and plank tests post-workout (**Chapters 2 and 3**). These findings underscore the importance of ensuring adequate recovery between successive Fran sessions (Tibana et al., 2018; Sousa Neto et al., 2022).

The studies described above (**Chapters 2, 3, 4 and 5**) were useful for gathering the knowledge needed to analyze cardiorespiratory and bioenergetic in different CrossFit® benchmark workout. Thus, the aim of the **Chapter 6** was to characterize the $\dot{V}O_2$ kinetics, estimate the energy systems contributions, and evaluate the total energy expenditure during a CrossFit® Isabel workout performed in the extreme intensity domain (Hill et al., 2002). We found that the Isabel workout (typically performed in ~120 s) displayed $\dot{V}O_2$ kinetics characterized by a prominent fast component, with insufficient time for a discernible appearance of a slow component. This outcome is evidence indicating energetic demands in the extreme intensity domain (Hill et al., 2002; Ribeiro et al., 2015). Moreover, the velocity of muscle contraction during the Isabel workout led to increased cardiorespiratory and metabolic stress (evidenced by elevated EPOC, $[La^-]$ and $[Glu]$ levels) compared to baseline, ultimately affecting the return to homeostasis. These outcomes align with those observed in **Chapters 2, 3 and 5** indicating that CrossFit® workouts with a short duration of ~120-200 s can be effective in improving physical fitness.

Regarding the $\dot{V}O_2$ kinetics variables, this study revealed higher $\dot{V}O_2$ amplitudes (42.0 and 35.8 mL·kg⁻¹·min⁻¹) compared to those observed in the unbroken Fran workout (**Chapter 3**). In contrast, the mean value of the time constant (14.2 and 23.7 s) was higher in the unbroken Fran workout, with no differences in the time delay (4.3 and 4.7 s) between the two workouts. These differences can be attributed to the higher values of $\dot{V}O_2$ reached in the extreme domain (higher O₂ demand), since as the effort intensity increases, the amplitude gains are higher. The differences observed in the time constant can be attributed to the intense nature of Isabel workout regimen, reflecting the adaptation profile of the cardiovascular and muscular systems to the

corresponding intensity (Markovitz et al., 2004). In fact, the high contraction velocity likely caused a swift rise in ATP demand, leading to $[La^-]$ accumulation (e.g. $1.5\text{-}20.7\text{ mmol}\cdot\text{L}^{-1}$), given the immediate involvement of both type I/II muscle fibers (Kramer et al., 2017).

Gaining a better understanding of the metabolic profile of crossfitters is crucial for designing effective training programs and improving physical fitness (Reis et al., 2011; Kramer et al., 2017). The results presented in **Chapter 6** demonstrate an immediate and abrupt rise in $\dot{V}O_2$ at the onset of the workout, which continued to increase steadily until the completion of the session, underlining the contribution of the aerobic energy pathway even at extreme intensities. In fact, at this intensity domain, the three energy pathways accounted for 40, 45 and 15% of aerobic, anaerobic lactic and alactic energy contribution (respectively). Although the majority, approximately 60%, of the total energy was derived from oxygen-independent metabolism (combining lactic and alactic pathways), our findings indicate that even in short-duration ($\sim 120\text{ s}$) CrossFit® workouts, it is crucial to develop both aerobic and anaerobic capabilities to enhance overall performance.

To complement the findings outlined in **Chapter 6** and expand the biomechanical investigation into the extreme domain, **Chapter 7** analyzed kinetic and kinematic variables during the Isabel workout performed at maximal effort. The routine was analyzed globally and divided in initial, middle and final phases (10, 20 and 30 repetitions, respectively). This study focused specifically on changes in knee, hip and shoulder angles to provide a comprehensive understanding of the biomechanical aspects of extreme-intensity exercise. Maximal lift velocity and maximal lift power decreased from the initial to final phases, while the time from lift until the bar crossed the hip and shoulder decreased progressively along the Isabel workout. In addition, decrease in hip flexion was observed during the last two phases when the bar crosses the knee.

The power snatch exercise is a staple in CrossFit® programming and competitions, utilized in both focused training sessions (e.g. the Isabel workout) and metabolic conditioning routines (Tibana et al., 2016; Ribeiro et al., 2024). In the **Chapter 7** shifts in velocity and power production during the Isabel workout

were identified, underscoring the influence of extreme intensity workout on power profile. Despite observed declines in discrete biomechanical factors including hip flexion, crossfitters displayed adaptive pacing techniques to sustain performance levels amidst escalating fatigue. In fact, resistance exercise induced fatigue results in a transient loss of velocity and power producing capacity (Sánchez-Medina & González-Badillo, 2011). Moreover, given the standardized external load (61 kg) and repetition (30 repetitions) in Isabel workout, crossfitters manage the tempo of muscle contractions to moderate exercise induced fatigue (Ribeiro et al., 2024), reflecting the dynamic adjustments in movement mechanics throughout the Isabel workout. It appears that the primary cause of angular changes can be attributed to a potential lower limbs fatigue, which result in a reduction of lift velocity and the associated decrease in power observed in the last two phases.

Chapter 9 Conclusions

Based on the findings obtained in the experimental moments described in this thesis, it is pertinent to emphasize the following conclusions:

- I. Few studies have evaluated cardiorespiratory and bioenergetic variables in experienced crossfitters within the ecological setting of real-world training (as opposed to controlled environments such as treadmill running, cycling or rowing) employing comprehensive direct measurements of $\dot{V}O_2$.
- II. Methods for proper assessment of cardiorespiratory (e.g. $\dot{V}O_2$ kinetics) and bioenergetics were employed for the first time in CrossFit® workouts.
- III. The mode in which the Fran workout is performed (whether intermittently or unbroken), significantly impacts cardiorespiratory values (e.g. peak $\dot{V}O_2$ and HR), as well as bioenergetic contributions. The absence of differences in hemodynamic and metabolic function between the sexes indicates that the variation in physiological response during acute Fran workout between male and female is influenced by peripheral adaptations.
- IV. The observed increase in metabolic responses and perceived exertion, along with the decrease in performance on the countermovement jump and plank tests post-Fran workout, underscores the importance of allowing for sufficient recovery between successive Fran sessions.
- V. The analysis of $\dot{V}O_2$ kinetics reveals a greater amplitude of the fast component in Isabel workout compared to unbroken Fran workout performed at maximal effort.
- VI. The time constant of the fast component response is longer in the unbroken Fran workout compared with Isabel workout performed at maximal effort.
- VII. The time delay of $\dot{V}O_2$ kinetics the fast component response is similar in crossfitters compared to both unbroken Fran and Isabel workouts performed at maximal effort.
- VIII. No differences in anaerobic alactic contribution were observed between the $Ana_{recovery}$ and Ana_{Pcr} methods, suggesting that both approaches can

be utilized to estimate anaerobic alactic contribution during a CrossFit® workout performed at maximal effort.

- IX. The inclusion of the anaerobic alactic contribution is necessary to adequately assess the total energy expenditure, as omitting it can lead to an underestimate of about 15%, particularly in extreme intensity domain (like the Isabel workout).
- X. The Isabel workout (performed in ~120 s), elicits a substantial and effective cardiorespiratory response. This regimen could serve as an excellent training option for optimizing both oxygen-independent metabolism and oxidative phosphorylation pathways.
- XI. The Isabel workout induces alterations in total lifting time, velocity and power output throughout the workout, underscoring the influence of extreme intensity exercise on power profiles.
- XII. Despite the reduction in certain biomechanical variables along Isabel workout, such as hip flexion, crossfitters exhibited adaptive pacing strategies to sustain performance levels amidst escalating fatigue.

Chapter 10 Recommendations for future research

The thesis examined physiological and biomechanical aspects of Fran and Isabel CrossFit® benchmark workouts. Based on our main findings, it would be important to continue researching in this field or work, particularly these ideas:

- I. Extend the physiological and biomechanical analysis to encompass various types of CrossFit® benchmark workouts (e.g. Nancy, Grace, Linda and Chelsea).
- II. Investigate and compare cardiorespiratory responses and energy utilization among distinct level of crossfitters and sexes during CrossFit® workouts.
- III. Incorporate surface electromyography alongside physiological, kinematical and external kinetic assessment can enhance the understanding of muscular adaptations in terms of amplitude, frequency and coordination during workouts performed at maximal effort.
- IV. Integrate the assessment of fatigue factors (e.g. countermovement jump and plank test) with biochemical parameters (e.g. creatine kinase).
- V. Analyze fatigue status and recovery in response to CrossFit® workouts over several days using similar methods to further our understanding of performance changes and fatigue and recovery markers among different levels of crossfitters and sexes.
- VI. Investigate the effects of prescribed training interventions over weeks in response to consecutive days of CrossFit® training, utilizing similar methods, are crucial for a comprehensive understanding of accurately quantifying and monitoring CrossFit® training load.

Chapter 11 References

Chapter 1

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