Universidad Miguel Hernández de Elche

Programa de Doctorado en Deporte y Salud

TRAINING ADAPTATIONS AND LOAD QUANTIFICATION IN HIGH-INTENSITY FUNCTIONAL TRAINING

Doctoral thesis

A dissertation presented by

D. Alejandro Oliver López

Directed by

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Adicionalmente, se incluye un estudio complementario: este estudio se encuentra actualmente en proceso de revisión por pares.

Este manuscrito se presenta en esta tesis como parte del trabajo desarrollado, aunque no forman parte oficial del compendio conforme al artículo 19.4.a de la normativa de doctorado de la Universidad Miguel Hernández.

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El Dr. D. Rafael Sabido Solana, director, y la Prof. Dr. D. Annette Schmidt, codirectora de la tesis doctoral titulada “*Training adaptations and load quantification in high-intensity functional training*”

INFORMAN:

Que D. Alejandro Oliver López ha realizado bajo nuestra supervisión el trabajo titulado “*Training adaptations and load quantification in high-intensity functional training*” conforme a los términos y condiciones definidos en su Plan de Investigación y de acuerdo con el Código de Buenas Prácticas de la Universidad Miguel Hernández de Elche, cumpliendo los objetivos previstos de forma satisfactoria para su defensa pública como tesis doctoral.

Lo que firmamos para los efectos oportunos, en Elche y München el 5 de mayo de 2025.

Director de la tesis	Codirectora de la tesis:
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El Dr. Francisco Javier Moreno Hernández, Coordinador del Programa de Doctorado en Deporte y Salud

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Prof. Dr. Francisco Javier Moreno Hernández

Coordinador del Programa de Doctorado en Deporte y Salud

“Aquí no acaba nada, aquí empieza todo.

Nunca encontré respuestas,

solo el inicio de nuevas preguntas.”

Oliver-López, Alejandro

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List of abbreviations

HIFT: High-Intensity Functional Training

CF: CrossFit

WOD: Workout Of the Day

AMRAP: As Many Repetitions As Possible

FT: For Time

HR: Heart Rate

VO2: Oxygen Uptake

[La]: Peripheral blood lactate

HRV: Heart Rate Variability

CMJ: Countermovement Jump

RPE: Rate of Perceived Effort

VO_2max: Maximum Oxygen Uptake

EMOM: Every Minute On a Minute

Rx: Prescribed workout standards

1RM: One repetition maximum

CJ: Clean and Jerk

TH: Thruster

TT: Tibana Test

PP/BW: Ratio Push Press 1RM / Body Weight

HRmean: Mean Heart Rate

HRpeak: Peak Heart Rate

RMSSD: Root Mean Square of Successive Differences

LnRMMSD: Logarithm of RMSSD

HS: High Strength

LS: Lower Strength

IG: Inexperienced Group

EG: Experienced Group

CA: Cluster Analysis

SL: Standardized Load

RL: Relativized Load

C: Clean

VO_2peak: Peak Oxygen Uptake

VO_2mean: Mean Oxygen Uptake

SWC: Smallest Worthwhile Change

BP: Blood pressure

HRmax: Maximum Heart Rate

FC: “Frecuencia Cardíaca”

List of figures

Nota: Las figuras insertadas en esta tesis doctoral son de elaboración propia.

Las portadas de los capítulos han sido elaboradas con la herramienta Canva (Almo Studio), combinando imágenes propias con diseños generados por inteligencia artificial (OpenAI, 2025).

Resumen

El entrenamiento funcional de alta intensidad (HIFT), y en particular su modalidad más extendida, CrossFit (CF), combina ejercicios funcionales propios de disciplinas como la halterofilia, la gimnasia o los deportes de resistencia, ejecutados a alta intensidad y con una estructura variada. El entrenamiento tipo CF se caracteriza por su naturaleza concurrente, al combinar estímulos de fuerza, potencia y capacidad cardiovascular en una misma sesión. Esta simultaneidad puede generar fatiga residual y afectar negativamente al rendimiento si no se gestionan adecuadamente la carga y la recuperación. Además, el carácter competitivo y abierto de CF, con un énfasis en el número de repeticiones y el tiempo total, dificulta la cuantificación precisa de la carga de trabajo, lo que complica la planificación y prescripción del entrenamiento.

Esta práctica ha ganado popularidad entre diferentes perfiles de usuarios que buscan mejorar su condición física, imagen corporal o bienestar general. Sin embargo, este tipo de entrenamiento es muy exigente y puede provocar respuestas fisiológicas intensas, incluso en practicantes experimentados. Esto dificulta valorar con precisión sus efectos sobre la salud y el rendimiento.

La presente tesis se estructuró en dos fases. En la primera, se llevaron a cabo dos investigaciones cuasiexperimentales de carácter transversal. En el primer estudio se analizó la respuesta aguda de los deportistas ante distintas modalidades de organización del entrenamiento de CF igualando la carga. En el segundo se comprobó si existían diferencias entre grupos al realizar un entrenamiento similar de CF con dos tipos de cargas: estandarizada y relativa.

La segunda fase consistió en una intervención longitudinal comparando las adaptaciones crónicas entre dos grupos de deportistas experimentados: uno siguiendo un programa con carga estandarizada y otro con carga relativa. Las respuestas y adaptaciones de corte fisiológico, neuromuscular y perceptivas fueron medidas antes y después de la intervención así como valores de rendimiento.

Por tanto, esta tesis busca aportar evidencia sobre los efectos del entrenamiento CF para optimizar su diseño y aplicación desde una perspectiva científica. El objetivo final es mejorar la eficacia y seguridad de este tipo de entrenamiento. Se busca garantizar respuestas adaptativas positivas en los usuarios, independientemente de su nivel o experiencia.

Palabras clave: Entrenamiento de fuerza de alta-intensidad, entrenamiento funcional, entrenamiento concurrente

Abstract

High-intensity functional training (HIFT), and in particular its most popular modality, CrossFit (CF), combines functional exercises from disciplines such as weightlifting, gymnastics or endurance sports, performed at high intensity and with a varied structure. CF training is characterized by its concurrent nature, combining strength, power and cardiovascular capacity in the same session. This simultaneity can generate residual fatigue and adversely affect performance if load and recovery are not properly managed. In addition, the competitive and open-ended nature of CF, with its emphasis on the number of repetitions and total time, makes it difficult to quantify workload accurately, which complicates training planning and prescription.

This practice has gained popularity among different user profiles seeking to improve their physical condition, body image, or general well-being; however, the high demands of this type of training can produce intense physiological responses even in experienced practitioners, making it difficult to accurately assess its effects on health and performance.

This thesis was organized into two parts. First, two cross-sectional experimental studies. The first aimed to analyze the acute responses of athletes to different ways of organizing CF workouts with the same training load; the second phase focused on comparing the responses between groups performing a CF workout with two types of loads: standardized and relative.

The second phase consisted of a longitudinal intervention implemented to compare the chronic adaptations between two groups of experienced athletes: one following a program with a standardized load and the other with relative load. Physiological, neuromuscular and perceptual responses and adaptations were measured before and after the intervention, as well as performance values.

This thesis aims to show how CF training works, making it better and safer based on scientific findings, so that all participants, no matter their skill level, can benefit positively from it.

Key words: High-intensity resistance training, functional fitness, concurrent training

1. BACKGROUND

1. Background

1.1 History and popularity

The athlete´s training underwent several changes throughout the middle of the 20th century because many sports needed structural and physiological adaptations for strength and cardiovascular demands. Exercise science began to emphasize the importance of force and cardiorespiratory endurance for overall physical fitness and success in competition. Furthermore, it was not until the 1970s that researchers such as Hickson (1976) investigated "concurrent training" and the responses. Concurrent training describes the interaction between strength and endurance training (see Figure 1) executed in the same or different sessions but within the same training plan (Hickson, 1980). Several authors have contributed to similar investigations, highlighting how simultaneous training modalities could interfere with one another, particularly in cases of high-intensity endurance work inhibiting strength gains (Dudley & Djamil, 1985; Sale et al., 1990). This phenomenon sparked decades of research into optimizing concurrent training for performance and health (Wilson et al., 2012).

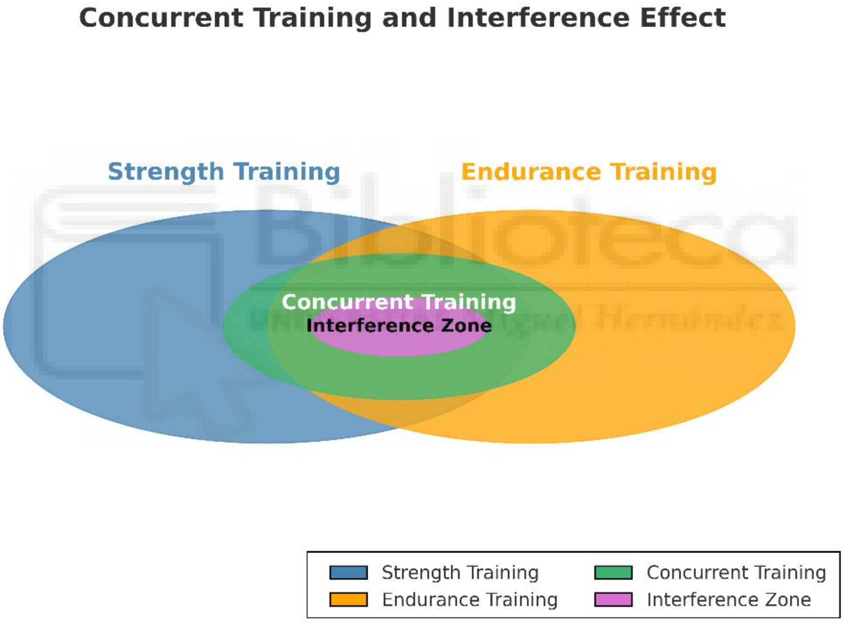


Figure 1. The phenomenon of interference in concurrent training.

In the 1980s and 1990s, exercise techniques like circuit training gained popularity by building on this basis and promoting an integrated approach that simultaneously improved several physical attributes. These ideas provided a foundation for more dynamic training programs that integrated multiple modalities into a single exercise regimen. In this context, CrossFit (CF) emerged as a revolutionary approach to fitness (Schlegel, 2020). Formally founded by Greg Glassman in 2000, CF built upon these concepts by combining functional movements, strength and endurance into a single training program. Glassman (Glassman, 2002), argued that the program focuses on functional movements performed at high intensity with multiple time domains to improve general physical fitness. CF became distinguished from previous concurrent training paradigms by rejecting linear periodization models and embracing unpredictability and diversity, in contrast to standard fitness programs (Glassman, 2004, 2005).

CF training initially had the goal of getting fit to lifeguards, firefighters, police officers, and army soldiers of the United States in a short length of time (Meyer et al., 2017; Paine et al., 2010). However, fitness enthusiasts quickly embraced this form of training and included these routines in their workouts, redefining themselves as "athletes" due to the ability of CF training to transform physical training into a competitive activity (Dawson, 2017). The ultimate goal of CF goes beyond exercise performance and aligns with the opportunity for body transformation and performance improvement (Crawford et al., 2018; Oliver-López et al., 2024).

CF's growth in popularity occurred in parallel with its transformation into a competitive sport. This training methodology was turned into a worldwide competitive event in 2007 with the CrossFit Games. According to Dawson (2017), athletes started training specifically for these competitions, changing their identities to competitive athletes. Moreover, from a sociological perspective, CF is more than just a fitness program or a sport modality, it is a way of life that emphasizes discipline, resilience, and community. Although CF has received praise for encouraging diversity and creativity in the fitness industry, it has also faced criticism, particularly regarding injury risk. Critics argue that the intensity of CF training may predispose participants to an improper technique or overtraining, which could result in an injury (Feito et al., 2018).

1.2 CrossFit overview

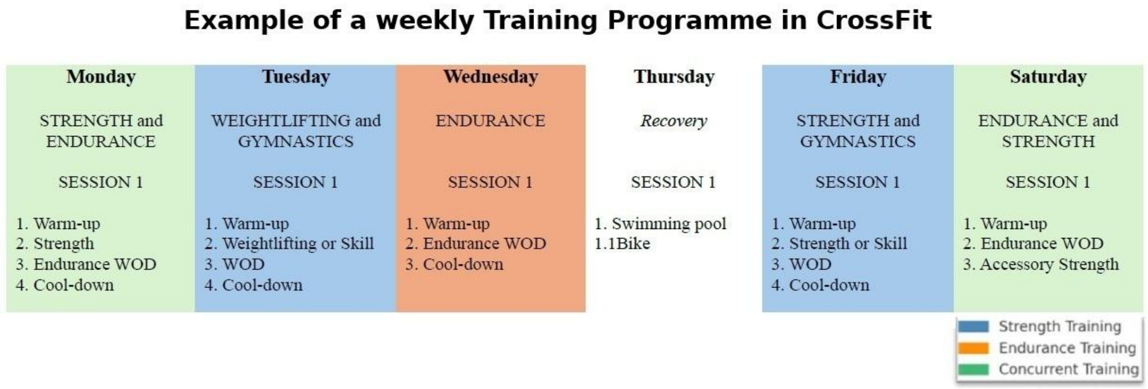
CF is an exercise modality that can be tailored to any fitness level and emphasizes multi-joint movements with high muscular recruitment. CF workouts known as "*Workout of the Day"* (WOD), combine anaerobic and aerobic training methods in intervals to enhance body composition and aerobic fitness (Murawska-Cialowicz et al., 2015). Generally, CF involves four sections in the training sessions: the warm-up, the strength or skill part, the WOD, and the cool-down. Their design combines movements from different disciplines, such as weightlifting (e.g. power clean), powerlifting (e.g. deadlift), gymnastics (e.g. muscle-up) and endurance (e.g. running) exercises (Tibana et al., 2018). Its designs vary daily but usually consist of a mixture of high-intensity exercises lasting 5-20 minutes and many repetitions requiring high muscular endurance strength (Drum et al., 2017; Tibana et al., 2021). Such characteristics can cause both novice and experienced athletes to engage in excessive training sessions (Weisenthal et al., 2014).

CF sessions are prescribed to achieve a high-intensity stimulus during the WOD part. While each session starts with a warm-up, which usually includes mobility drills, activation exercises and specific movements of the following part, it guarantees that participants are both neurologically and physically prepared (Bergeron et al., 2011; Glassman, 2002). After the warm-up, the sessions transition into a strength training or skill section. In this stage, the focus is on developing strength through basic lifts like squats, deadlifts, pushes or throws movements, or on mastering the technical aspects of complex moves like gymnastics exercises or weightlifting movements (Wagener et al., 2020). This section is usually individualized or scaled to each participant's capabilities, utilizing concepts such as progressive overload to drive future improvement.

Nevertheless, the core of each session is the WOD, the high-intensity challenge. One example is the circuit modality *As Many Repetitions as Possible* (AMRAP), such as the workout "Cindy", which combines pull-ups, push-ups and air squats in a structured sequence for 20 minutes. Another common example is the *For Time* (FT), exemplified by the workout "Fran", consisting of thrusters and pull-ups performed as quickly as possible. But these WODs are not the only ones that define the variety and intensity of CF, WODs such as "Murph" challenge endurance with the combination of running, pull-ups, push-ups and air squats, whilst the "CrossFit total" assesses maximal strength across the back squat, shoulder press, and deadlift (Claudino et al., 2018).

In the end, CF sessions conclude with a cool-down phase, facilitating the transition from the high-intensity demands of the workout to a state of recovery. This phase is designed to reduce the heart rate, promote muscular relaxation and aid in the body's return to homeostasis. CF coaches frequently employ several dynamics, including breathing exercises, passive stretching and active recovery methods. Breathing exercises, for example, diaphragmatic or controlled rhythmic breathing, can activate the parasympathetic nervous system, reducing stress and promoting relaxation (Balban et al., 2023). Passive stretching helps alleviate muscle tightness and improve flexibility, while active recovery, such as low-intensity cycling, can enhance blood circulation and facilitate the clearance of metabolic products like lactate (Dupuy et al., 2018). These strategies not only improve recovery efficiency but also reduce the risk of post-exercise soreness producing a pain-relieving effect (Fares et al., 2022).

From a training planning perspective, the CF program is adapted according to the experience or strength level of the participants. For beginners, or athletes without high strength levels, programming focuses on foundational movement patterns, skill acquisition, and moderate intensity for endurance components. These participants may attend CF training two or three times a week, usually with a recovery period of more than 48 hours to optimize adaptation and progressive incorporation into the group with less risk of injury (Claudino et al., 2018). In contrast, experienced athletes or those with high strength levels, follow a more advanced program, often structured as three following days of high intensity with one day for recovery training (like swimming or cycling at moderate intensity) and the other two days of CF training, only with one day for rest (see Figure 2). Usually, these athletes incorporate heavy strength training, high-skill gymnastics, and varied metabolic conditioning with specific CF goals (Pritchard et al., 2020). Also, independently of the participant level, CF programming alternates the three primary training modalities (strength, gymnastics and endurance) across sessions to enhance adaptations in fitness. Depending on the lesson of the day, these elements may be isolated to emphasize specific capacities or combined to create complex discipline movements, which improve physical fitness and reduce monotony during training (Glassman, 2003).



Example of a weekly Training Programme in CrossFit

Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
STRENGTH and ENDURANCE	WEIGHTLIFTING and GYMNASTICS	ENDURANCE	*Recovery*	STRENGTH and GYMNASTICS	ENDURANCE and STRENGTH
SESSION 1	SESSION 1	SESSION 1	SESSION 1	SESSION 1	SESSION 1
1. Warm-up 2. Strength 3. Endurance WOD 4. Cool-down	1. Warm-up 2. Weightlifting or Skill 3. WOD 4. Cool-down	1. Warm-up 2. Endurance WOD 3. Cool-down	1. Swimming pool 1.1Bike	1. Warm-up 2. Strength or Skill 3. WOD 4. Cool-down	1. Warm-up 2. Endurance WOD 3. Accessory Strength

🟦 Strength Training
🟧 Endurance Training
🟩 Concurrent Training

Figure 2. A week in a CF programme and the concurrent training modalities

1.3 Relevance of studying effects

CF training provides chronic adaptations based on the acute effects of its sessions, which depend on the usual physical training variables, such as magnitude, frequency and duration of the stimulus (Powers & Jackson, 2008; Wasfy & Baggish, 2016). In this regard, several authors have demonstrated that CF training results in a greater acute response to cardiovascular training as well as a notable improvement in fitness levels (aerobic and anaerobic performance) ´ (Butcher et al., 2015; Paine et al., 2010). This modality of physical training, known for its high intensity, elicits acute responses in physiological variables such as significant increases in heart rate (HR), oxygen uptake (VO_2), blood lactate levels [La] and altered pro- and anti-inflammatory cytokines heightened oxidative stress. Other observed effects include elevated peripheral body temperature, post-exercise blood pressure, increased blood glucose levels, and decreased heart rate variability (HRV) responses typical of intense training stimuli. Other acute effects were reflected in the neuromuscular and perceptual responses of participants when performing a countermovement jump test (CMJ) or a reaction time test, without forgetting the subjective responses of the participants such as the perceived effort (RPE) or how it affects their mood, as represented in Figure 3 (Butcher et al., 2015; Maia et al., 2019; Perciavalle et al., 2016).

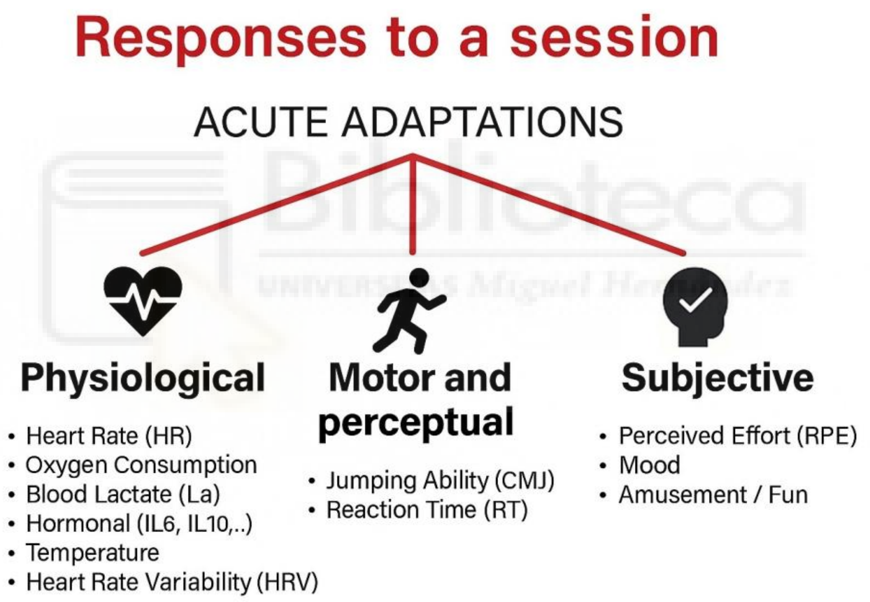


Figure 3. Acute adaptations of the participants to a high-intensity CF training session

Chronic adaptations to CF systematic training include improvements in aerobic capacity and VO_{2max} and blood pressure regulation, particularly in novice participants and young athletes, reflecting improved cardiovascular efficiency and oxygen transport capacity (Borras et al., 2017). Experienced athletes demonstrate higher aerobic capacities, enabling them to sustain greater absolute workloads and these adaptations highlight the impact of sustained high-intensity training over time. Moreover, at the long-term hormonal level, CF training promotes anabolic processes, neurogenesis, and adipose tissue mobilization, with studies reporting increased testosterone levels and a decrease in cortisol, leading to an improved testosterone-cortisol ratio (Fealy et al., 2018; Mangine et al., 2020; Murawska-Cialowicz et al., 2015). In this context, this high-intensity functional training drifts into many hormonal changes following a regimen of resistance training combined with endurance training in a system of maximal concurrence. Moreover, the performance in CF correlates with an optimal body composition, which may be influenced by the need to perform strength movements as fast as possible. This training demand may be influenced, among other factors, by an increase in muscle cross-sectional area, a reduced body fat percentage, and a somatotype shift towards mesomorphic predominance (Mangine et al., 2020). Performance improvements are also evident in enhanced mobility, flexibility, strength, power, and motor efficiency. This enables athletes to sustain higher workloads, especially in experienced CF participants, who are most likely to develop these performance-determining qualities (Cejudo, 2022; Mangine et al., 2020a; Meier et al., 2023). Lastly, psychological adaptations encompass the basic physiological needs (autonomy, competence and relatedness), promoting adherence to CF training (Dominski et al., 2021; Ryan & Deci, 2000). Nevertheless, excessive training can lead to negative behaviours such as exercise addiction and body dissatisfaction (Oliver-López et al., 2024). These combined adaptations illustrate the complex physiological, structural, performance and psychological chronic responses to sustained CF training (see Figure 4).

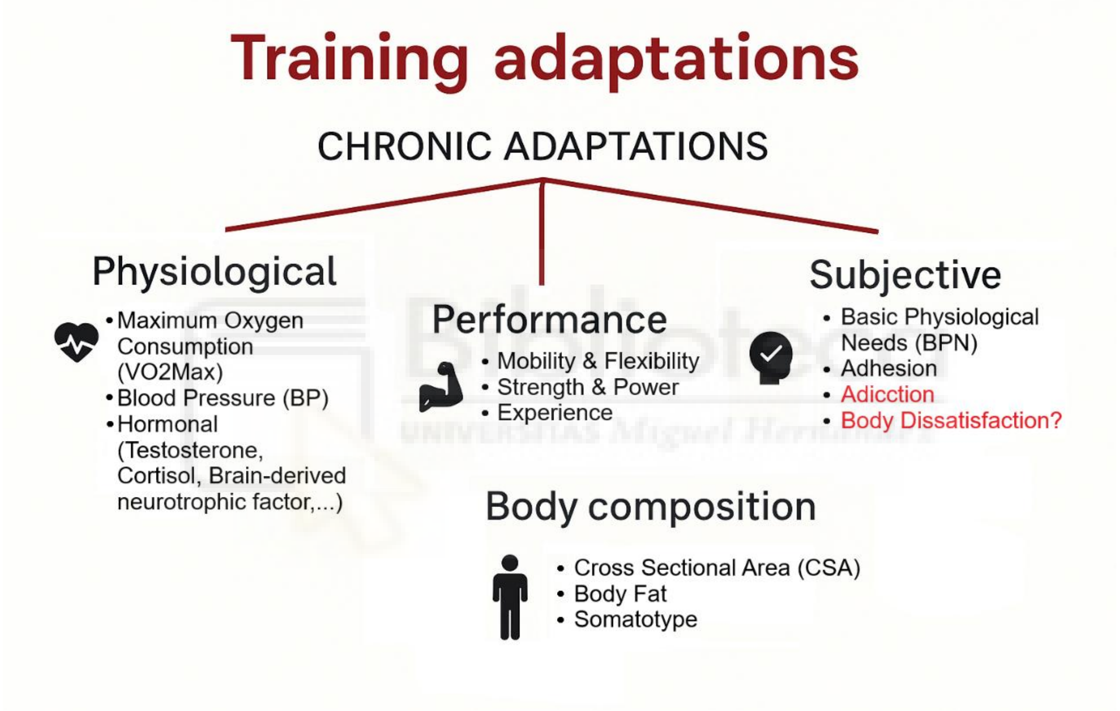


Figure 4. Chronic adaptations of participants to systematic CF physical training

This whole swarm of adaptations at the acute and chronic levels show us the significant impact on the endocrine, immune and central nervous systems, while also contributing to the development of key physical parameters such as strength and endurance. These benefits are linked to a training methodology that develops attributes like speed, power, and other specific CF-related skills (Schlegel, 2020). Nevertheless, not forgetting that there are also reported cases of overtraining and injuries due to over-stimulation derived from high-intensity practice, resulting in well-known maladaptations. Tibana et al. (2016) reported elevated cortisol levels and reduced testosterone-cortisol ratios in athletes engaging in excessive CF workouts, indicating a hormonal imbalance associated with overtraining.

1.4 Different WODs, different responses

Designing successful CF sessions requires a basic understanding of the bioenergetics underlying different workout modalities. In whatever CF box, athletes can perform CF training with any of the three main types of structure according to the aim, but with a specific conditioning factor, the time. Depending on this factor, WODs are classified with a structure based on a time limit for all exercises, as AMRAP distribution, or that encourages athletes to complete the workout as quickly as possible in a workout FT. Therefore, both instructions are frequently focused on the overall timing of WOD (Mullins, 2015). Moreover, the interval training method known as *Every Minute On Minute* (EMOM) is characterized by the design of time windows in which athletes are compelled to keep a tempo by round, as a result, faster performance may result in a longer rest period (Smith et al., 2025).

The three main CF workout distributions and the aim of this part, differ significantly in their configuration and the ability to predict task endpoints. In AMRAP and EMOM workouts with fixed total time, the endpoint is determined by the task's duration, yet in FT sessions, the endpoint is defined by completing a set volume of exercises (see Figure 5). For endurance exercise, metrics like distance or total calories at the ergometer cover help quantify performance. Conversely, strength or gymnastic movements rely on repetitions, sets or rounds as performance indicators (De-Oliveira et al., 2021). Notably, the FT model with a time cap offers the greatest predictability of outcomes by providing both the time limit and task volume, and this predictability can be influenced by factors such as the fitness athlete, their pacing strategy, their experience, etc.

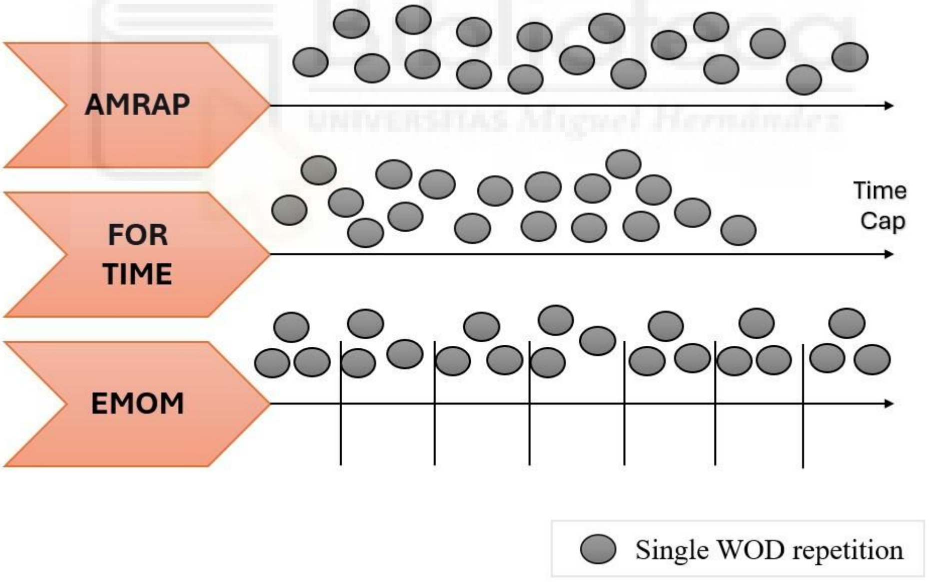


Figure 5. Three main CF workout distributions with different time domains and the same repetitions

AMRAP, FT, and EMOM generate distinct physiological and psychological responses heavily influenced by the level of experience practicing CF and strength capacity. On the one hand, the modality FT should be the highest intensity reflected in the higher level of HR recorded and the blood lactate level compared to AMRAP (Timón et al., 2019). On the other hand, less experienced athletes or those with lower strength levels may exhibit quicker onset of fatigue during high-volume AMRAP sessions due to inefficiencies in movement and energy use, whereas more experienced individuals might adopt refined pacing strategies that enhance their performance and recovery dynamics (Barba-Ruíz et al., 2024; Chidnok et al., 2013).

1.5 CrossFit prescription

CF stands out as a novelty training modality focused on preparing athletes for the unknown, utilizing a variety of "functional" exercises to improve adaptability and overall fitness (Meier et al., 2023). The underlying idea is that CF athletes should be prepared for any physical challenge, regardless of its nature. However, while this approach can be effective for some goals, the key to maximizing the benefits of a training program lies in the correct application of fundamental programming principles.

To guarantee that training sessions are effective, coaches should bear in mind a variety of variables when designing an individualized training prescription. These variables include weekly training frequency, session duration, the different parts of a CF session (e.g., warm-up, workout, cool-down), as well as the proper training variables, such as intensity, volume, and rest time between sets and exercises. Nevertheless, the challenge in CF arises when these parameters are applied uniformly to all participants, disregarding the diversity of strength, gymnastic skills, and experience among CF practitioners.

CF training is an example that effectively incorporates variation, different and innovative movements, and high-intensity exercise to keep athletes motivated and improve their capacity to adapt to any challenges. Nevertheless, it is inconsistent with other principles or basic training guidelines, such as progressive overload or individualization. The diversity in CF athletes (strength levels and CF experience) demands that training programs be designed to each need. Although different versions on some occasions address these differences, the fact that the same workouts with standard barbell loads are given to all participants can hinder the progress of advanced athletes or those who want to improve their fitness.

This brings us to the following situation: while CF programming allows for different workout options, participants often don't choose the right weight for each WOD, which can hinder their progress. The principle of progressive overload says that training weights should gradually increase to keep improving. If athletes don't get the right weights for their training sessions, they might stop seeing improvements or risk overtraining from lifting too much, which can slow down their long-term progress (Montalvo et al., 2017).

Despite these issues, CF remains an excellent example of how training variation, through diverse movements, exercise combinations, and high-intensity approaches, can keep athletes engaged and promote greater adaptability to any challenge. However, it is important to recognize that the effectiveness of this approach is limited if other key training principles, such as specificity, progressive overload, and individualization, are not adequately integrated (Suchomel et al., 2021). Therefore, to optimize adaptations in CF participants, coaches be mindful of the importance of selecting training variables according to every athlete's capacity, which not only involves variation and novelty but also ensures that load and intensity are progressive and adjusted to each athlete regardless of their level.

1.6 A lack of individualisation

The inherent structure of CF training is designed around the WOD, as it is the main element of competition. The WOD is similar for all participants but with many differences regarding the barbell weight or the gymnastic movements. Nevertheless, these modifications do not fully account for each individual's fitness level, goals, or limitations. These modifications are sometimes preestablished, and it may be the case that a novice practitioner is unable to perform the movements of an easy version or lift the barbell weight of a lighter standard.

In terms of CF, the athletes can perform the WODs in the prescribed or *Rx* version (following the prescribed standards of weight for strength exercises, determined gymnastic movement, and the distances or calories for the endurance part) or choose the *scaled* version (following a standard of lighter weight, easier gymnastic movement and less distance or calories for the endurance part than the *Rx* athletes). However, training prescriptions with these criteria of two standard levels for participants with different characteristics could be excessive for some and inefficient for others who already have a high level of performance. Advanced athletes may find the *scaled* version too easy, while the *Rx* version may be too challenging for those still building their fitness (Mangine et al., 2021).

In addition, benchmark WODs, originally designed with standardized movements and established barbell loads to assess performance, are commonly used by CF coaches as part of the regular training sessions, rather than being reserved exclusively for testing athletes. For example, the WOD "Isabel" consists of 30 snatches with 60 kg for males and this standard could have different implications depending on the 1RM of an athlete in the snatch. On the one hand, for an athlete with a 110 kg 1RM in the snatch, performing 30 repetitions (55% of their maximum) would likely demand a great deal of energy and could lead to significant muscular fatigue, affecting their performance and recovery. On the other hand, for an athlete with a 75 kg 1RM (80% of their maximum), this load would be much more demanding, likely leading to rapid muscle fatigue, poor form technique, and potentially increased risk of injury, as their strength capacity is not adequate to lift this weight for 30 repetitions. In both cases, the prescribed load fails to align with the individual strength capacities of the athletes, highlighting the necessity of individualizing the load in CF WODs as represented the Figure 6.

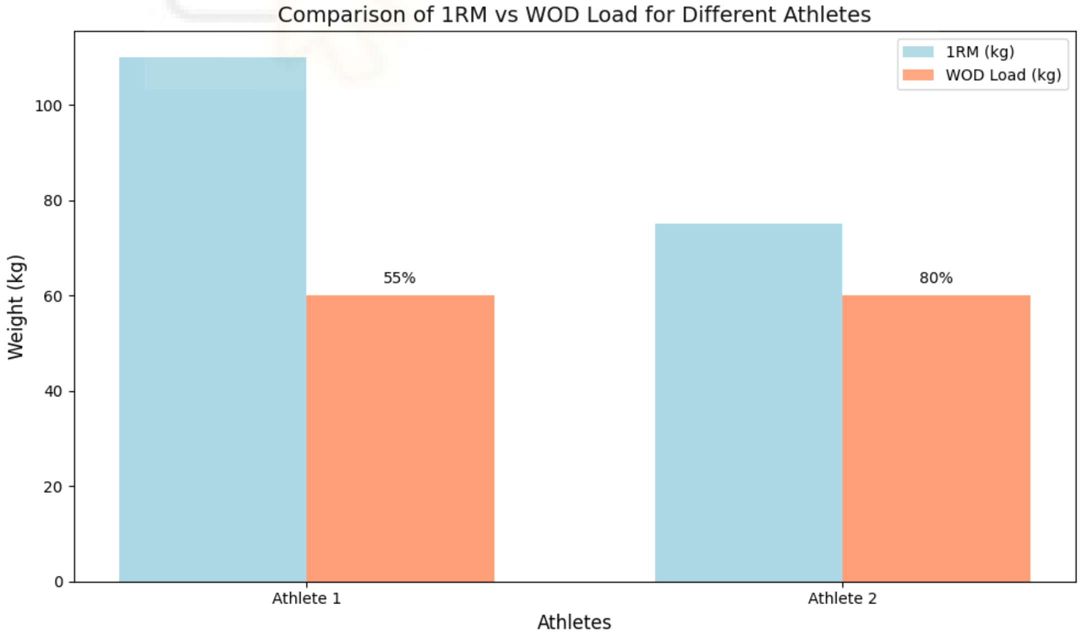
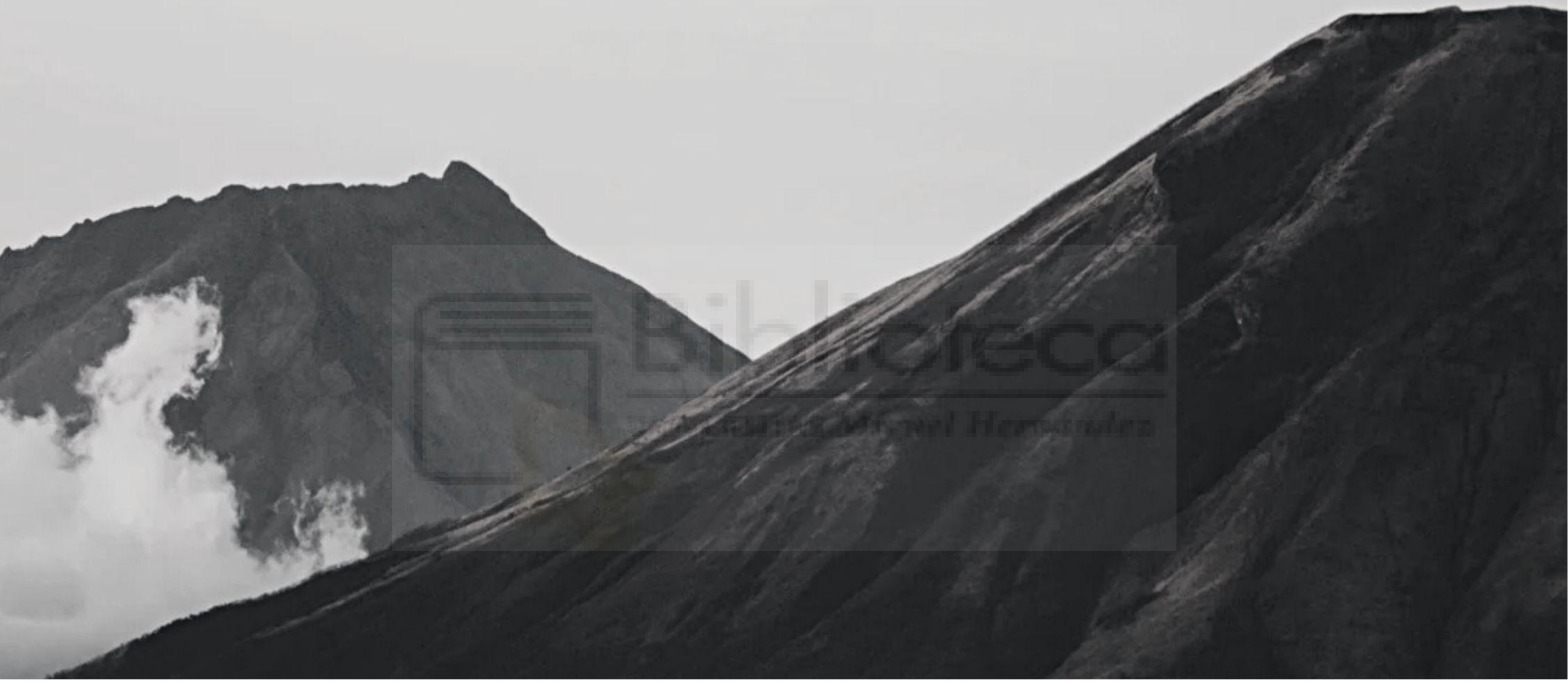


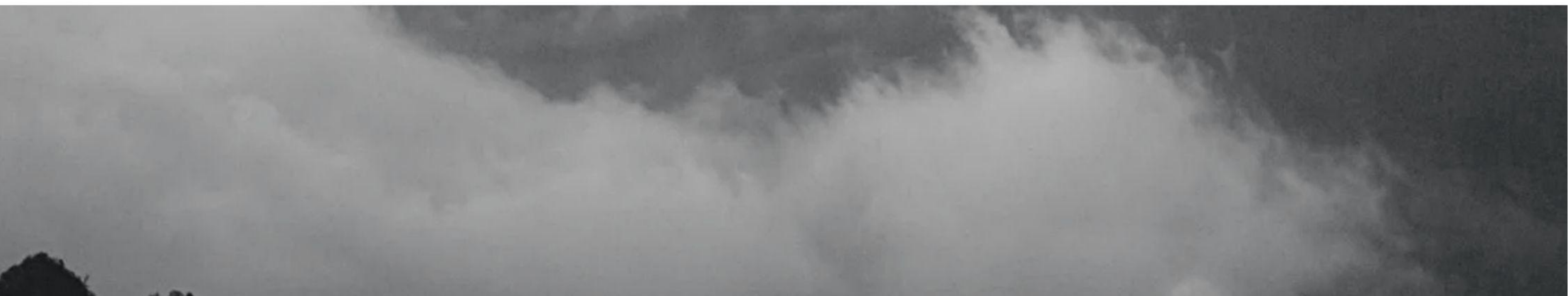
Figure 6. WOD "Isabel" barbell weight and differences in their %1RM of the snatch for two male athletes

1.7 Summary of the research problems

The emergence of this high-intensity training in the last 25 years and its worldwide reach in all populations has placed the focus of sports researchers on CF methods and their particular systems to improve fitness. Generally, the main approaches to this discipline have focused on injury incidence, determinants of performance, and psychological effects, giving a general vision of CF training, focusing on participant safety and subjective adaptations (Dominski et al., 2021; Martínez-Gómez et al., 2019; Rodríguez et al., 2022). However, the present thesis aims to address several research problems: i) Understanding the training responses and adaptations resulting from CF training. ii) Investigating the impact of different WOD structures (AMRAP, FT, and EMOM), where the dominance of time over repetitions complicates the accurate control of training load in athletes. iii) Developing strategies for prescribing individualized intensity during strength movements in CF workouts, rather than relying on standardized loads, to help coaches optimize training responses and adaptations in CF participants.

2. RESEARCH OBJECTIVES AND HYPOTHESES





2. Research objectives and hypotheses

2.1. General objectives

The research problems previously identified in CF training reveal a considerable gap in understanding a holistic context of the responses and adaptations derived from this concurrent training and the diverse structures of their WODs. Moreover, this discipline often lacks control over training variables such as volume, density and, in particular, intensity. This thesis explores the optimization of intensity by individualizing barbell load in resistance exercise-based WOD movements, addressing the limitations of the current prescribed and scaled versions, which often overlook individual differences in strength capacity, CF experience or fatigue response. This misalignment underscores the need to refine strength training prescriptions in CF by tailoring loads and intensities more accurately to each athlete's specific profile.

Studies 1, 2, 3 and 4 were performed to achieve these objectives. *Study 1 aimed* to elucidate the acute impact on athletes, considering the experience, when performing the three typical modalities (AMRAP, FT, and EMOM) with matched training loads. *Study 2* aimed to compare both performance and acute responses concerning the participants' strength levels (high strength and lower strength), by contrasting the effects of individualized vs. standardized barbell loads during a similar WOD. *Study 3* intended to explore the relationship between the clean and jerk (CJ) 1RM and the maximum repetition in the thruster (TH) in CF participants, as well as assess the influence of gender and training experience. *Study 4* aimed to compare, through a CF intervention, the effect of relativized barbell loads vs. standardized Rx loads on CF performance and several adaptations. Specifically, the differences in performance and participants´ responses during the Tibana Test (TT) under laboratory conditions were examined before and at the end of this study.

2.2. Specific objectives

The order of the four studies in this doctoral thesis guides the organization of this section.

2.2.1. Study 1

1) The study aims to analyze the acute effects of three different CF workout modalities with similar volume and relative load in CF participants.

2) To compare the acute responses to the three CF workout modalities based on the participant's experience level in CF training (experienced vs. beginner).

2.2.2. Study 2

3) To evaluate the performance measure in total repetitions when the same WOD is performed with a standardized or individualized load prescription.

4) To analyze and compare the acute responses to standardized or individualized load prescription based on participant´s strength levels (high strength vs. lower strength)

2.2.3. Study 3

5) The goal of the study is to determine the relationship between the 1RM of the CJ and TH maximum load in CF athletes based on gender and experience level in CF training.

6) The objective is to establish prediction equations for TH performance based on CJ performance, considering gender and experience level.

2.2.4. Study 4

7) To evaluate differences in maximum strength measured through 1RM following a CF intervention in standardized and relativized load groups.

8) The study aims to analyze changes in TT performance, including physiological, neuromuscular, and subjective variables after the CF intervention in standardized and relativized load groups.

2.3. Hypotheses

According to the findings of previous research, a set of hypotheses was formulated across the four studies of this doctoral thesis:

- **Hypothesis 1:** FT workout design will produce higher physiological and psychological responses than AMRAP and EMOM structures, regardless of the training volume and total load.
- **Hypothesis 2:** Experienced and beginner participants will exhibit significant differences in their performance and acute responses when performing FT, AMRAP, and EMOM workouts with a similar volume and relative load.
- **Hypothesis 3:** Relative barbell loads based on each participant's strength level will not result in statistically significant differences in WOD performance between groups with different strength levels. In contrast, standardized barbell loads will result in significant differences in performance between these groups.
- **Hypothesis 4:** Participants with different strength levels would exhibit similar acute responses when performing a WOD with a relative load compared to standardized WODs.
- **Hypothesis 5:** There will be a significant relationship between 1RM of the CJ and TH maximum load in CF athletes, with the strength of the correlation varying based on gender and experience level.
- **Hypothesis 6:** Prediction equations for TH performance based on CJ will be more accurate in participants with more than two years of CF training, regardless of gender.
- **Hypothesis 7:** The Relativized load group will show more improvement in time trial performance and maximum strength, measured by 1RM and CMJ fatigue, after the CF intervention compared to the Standardized load group.
- **Hypothesis 8:** Standardized and Relativized load groups will show similar efficient reactions during TT, including physical fatigue, muscle fatigue, and personal feelings, after finishing the CF intervention.

3. SUMMARY OF THE METHODS

3. Summary of the methods

3.1 Studies 1 and 2, descriptive cross-sectional: modalities effects and standardised vs relativised

3.2.1 Participants

Twenty-five participants were enrolled in Study 2 (15 males and 10 females) from several CF boxes. The inclusion criteria were to have more than three months of experience and to perform CF training at least three times a week. Exclusion criteria included having less than three months of CF experience, having a metabolic disorder, cardiovascular disease or musculoskeletal injury that could affect the participants' health or the study tests, taking medication or supplements that could affect the measurements or not resting for at least 72 hours after the last training test. Nevertheless, the aggrupation criterion in Study 2 was based on the participant's experience performing CF training. Following different previous studies, the 24 months of experience was the cut-off value for grouping participants into the experienced group (age: 37.86±8.44 years, height: 167.50±4.50 cm, weight: 68.94±7.0 kg, CF experience: 74.21±41.42 months, PP/BW: 1.04±0.14 ratio) or the beginner group (age: 28.89±5.63 years, height: 170.01±9.80 cm, weight: 73.42±11.71 kg, CF experience: 19.10±6.48 months, PP/BW: 0.82±0.18 ratio) ´ (Durkalec-Michalski et al., 2019; Feito, Giardina, et al., 2018a; Mangine et al., 2020a; Mangine & Seay, 2022; Menargues-Ramírez et al., 2022).

Thirty-five participants were enrolled in Study 1 (17 males and 18 females). To be included, participants had to engage in CrossFit training a minimum of three times per week, and to have more than three months of experience in this training modality. The exclusion criteria were: i) having a metabolic disorder, cardiovascular disease or musculoskeletal injury that could affect the health of participants or the study tests (e.g. muscle strains, contusions, etc.); ii) taking drugs or supplements that could affect the measurements (e.g. caffeine or benzodiazepine); and iii) not have rested for at least 72 hours after the last training testing. In addition, for this second study, we assigned participants depending on their maximal lift in the push press movement divided by their body weight (P.P./B.W.=Ratio). For male participants, the cut-off value of the ratio was 1.1 and for females 0.8 for belonging to the higher strength group (age: 34.0.6±7.89 years, height: 166.31±7.03 cm, weight: 64.12±10.30 kg, CF experience: 56.71±35.01 months, PP/BW: 1.03±0.13 ratio) or the lower strength group (age: 33.14±7.04 years, height: 171.01±10.30 cm, weight: 75.69±13.80 kg, CF experience: 33.20±30.40 months, PP/BW: 0.85±0.17 ratio) ´ (Soriano et al., 2020).

3.2.2 Protocols

For Study 1, all participants signed a form saying they agreed to take part before joining and came to the lab four times, with at least 72 hours in between each visit without any physical training. The warm-up included five minutes of jogging, three sets of 10 joint mobility exercises (like lunges with a twist, pull-downs with a resistance band, and push-ups), and two sets of increasingly difficult WOD exercises at the start of each session. Participants had to do as many push press repetitions as they could, 72 hours after the first session (Bishop et al., 2008). This 1RM session followed the guidelines of Baechle & Earle (2002). In this study, the first WOD was the AMRAP, and based on the total repetitions from each participant, the load for their FT workout was determined. The FT required participants to finish the same load as fast as they could. Finally, the EMOM session kept the total load but divided it as follows: i) 1st minute for weightlifting; ii) 2nd minute for gymnastic exercises; and iii) 3rd minute for running (see Figure 7).

In Study 2, participants came to the lab three times, with 72 hours in between each visit, after agreeing to take part. The warm-up was the same as in the second study mentioned earlier. The 1RM for the push press was measured between the first and third sessions to adjust the weight for the last workout. The first and third sessions were workout days. In the first session, participants did an AMRAP workout with a set weight for both men and women (standardised WOD), and in the third session, they did the same type of workout but with 75% of their 1RM for the push press (relativised WOD) (see Figure 8).

The testing method was the same for both studies, except the second study did not include the HRV measure. Performance was monitored by two coaches, who recorded total repetitions in AMRAP, completion time in FT, and rounds in EMOM, making sure everything was done correctly. Participants rated their effort after workouts using the Borg CR-10 scale for RPE. Metabolic fatigue was measured by taking [La] samples from the left earlobe before the workout and 90 seconds after exercising. Maximum jump height was tested with the CMJ test, where participants did six warm-up jumps followed by three maximum jumps (with hands on hips and full knee and ankle extension when landing), and the highest jump was noted for analysis. Heart rate was tracked with a chest monitor, recording HRmean and HRpeak. HRV was measured before and after the workout, with participants sitting for five minutes before the measurement, and data collected for one minute while breathing normally; the natural logarithm of RMSSD (LnRMSSD) was used as a sign of fatigue, shown as percentage changes before and after exercise.

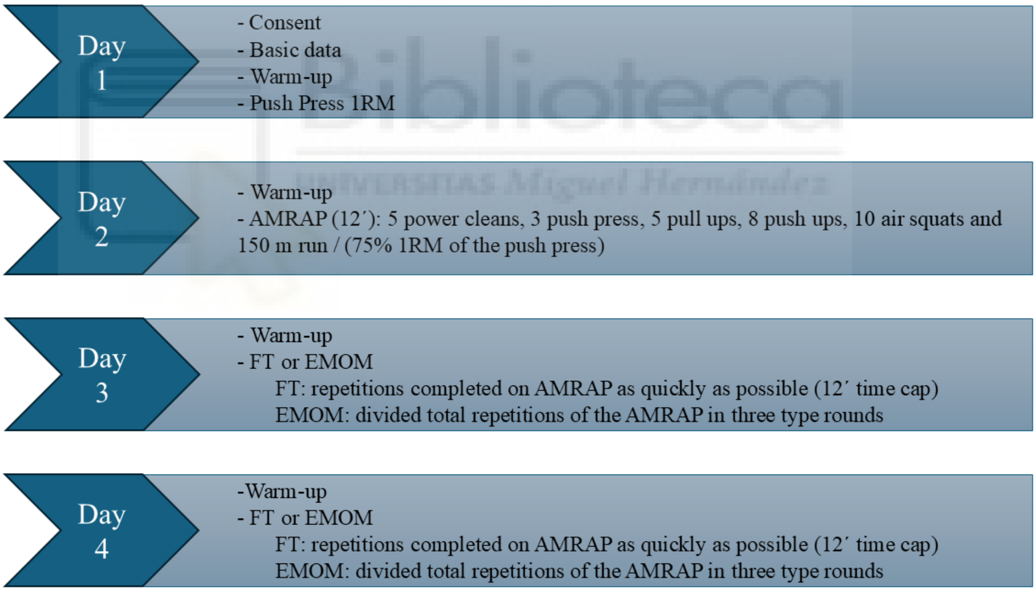
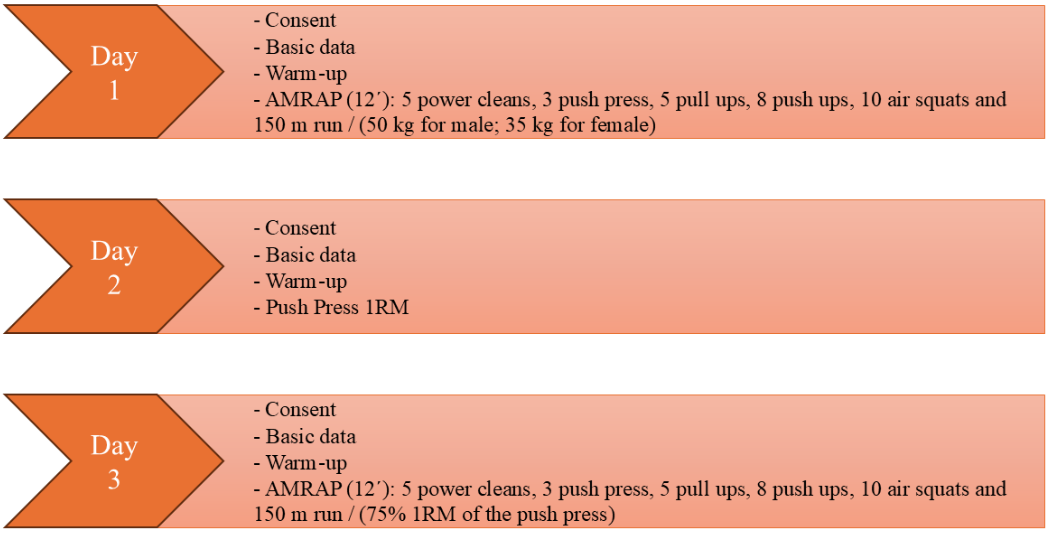


Figure 7. Scheme protocol of Study 1



- Consent
- Basic data
- Warm-up
- AMRAP (12´): 5 power cleans, 3 push press, 5 pull ups, 8 push ups, 10 air squats and 150 m run / (50 kg for male; 35 kg for female)

- Consent
- Basic data
- Warm-up
- Push Press 1RM

- Consent
- Basic data
- Warm-up
- AMRAP (12´): 5 power cleans, 3 push press, 5 pull ups, 8 push ups, 10 air squats and 150 m run / (75% 1RM of the push press)

Figure 8. Scheme protocol of Study 2

3.2.3 Statistical Analysis

For Study 1, the analysis and figures were designed using RStudio (v4.0.2). Performance was compared in WODs throughout the unpaired t-test between two groups: Inexperienced Group (IG) and Experienced Group (EG) in variables of performance and RPE. Moreover, we used a two-way analysis of variance (ANOVA with two factors: workout and expertise level with three and two levels, respectively) to compare the data reflecting WODs. We performed pairwise comparisons based on the Bonferroni criterion when any main effect was observed. Besides, we checked ANOVA assumptions by normality, homoscedasticity, and independence tests (Shapiro-Wilk, Levene, and Durbin- Watson tests, respectively). Additionally, a spreadsheet was used to calculate the effect magnitude based on Hedges' g, which the modified Cohen´s criteria interpreted: very small (< 0.10), small (0.10–0.29), moderate (0.30–0.49), large (0.50–0.69), very large (0.70–0.89), or extremely large (> 0.90) relationship (Hedges, 1981; Hopkins et al., 2009). Besides, Cohen´s f large effect size (Cohen, 1988) served as the theoretical framework for the a priori sample size analysis, which set statistical power at 0.8, and alpha at 0.5 for an estimated recruitment of participants. A p-value < 0.05 was considered a threshold for statistical significance.

For Study 2, analysis and figures were designed using RStudio (v4.0.2). Pearson's correlation was used to quantify the relationships between the categorised variables (PP/BW ratio and performance in both WODs) and modified Cohen's criteria very small (< 0.10), small (0.10–0.29), moderate (0.30–0.49), large (0.50–0.69), very large (0.70–0.89), or extremely large (> 0.90) relationship were used to analyse the correlations (Hedges, 1981; Hopkins et al., 2009). Afterwards, two factors were used to analyse variance (two-way ANOVA with two levels: standardised or relativised WOD, and high strength [HS] or lower strength level [LS]). The Bonferroni criterion was used for pairwise comparisons. The normality, homoscedasticity, and independence tests (Shapiro-Wilk, Levene, and Durbin-Watson tests, respectively) were used to verify the assumptions of the ANOVA, and all analyses passed. Additionally, a spreadsheet was used to calculate the effect magnitude based on Hedges' g, which Hopkins interpreted (Hedges, 1981; Hopkins et al., 2009). A p-value<0.05 was considered statistically significant.

3.3 Study 3, descriptive cross-sectional: Thruster movement prediction with Clean and Jerk 1RM

3.3.1 Participants

Seventy-three people took part in Study 3 (40 men and 33 women). They were CF participants with at least three months of experience, training a minimum of three times a week. Participants were included if they met these criteria: i) they were 18 years or older; ii) they were ready to do a maximum repetition test; iii) they had a metabolic disorder, heart disease, or muscle injury that could impact their health or the study tests (like muscle strains or bruises); iv) they were not taking any drugs or supplements that could influence the results (like caffeine or benzodiazepines); v) they had not rested for 24 hours before the 1RM test.

Participants were sorted in function of their gender and months of experience performing CF training, according to the criteria reported in the literature and used for the second study of the present thesis of 24 months of CF experience as the cut-off value (Durkalec-Michalski et al., 2019; Feito, Giardina, et al., 2018a; Mangine et al., 2020a; Mangine & Seay, 2022; Menargues-Ramírez et al., 2022). As a result, four groups were obtained: experienced men (age: 35.29±8.13 years, height: 175.87±8.49 cm, weight: 83.67±18.15 kg, CF experience: 72.13±33.45 months, 1RM thruster: 89.63±15.44 kg, 1RM clean and jerk: 98.29±18.69 kg), experienced women (age: 32.41±8.13 years, height: 164.58±5.35 cm, weight: 60.27±5.76 kg, CF experience: 63.29±24.35 months, 1RM thruster: 54.59±6.45 kg, 1RM clean and jerk: 59.00±9.74 kg), beginner men (age: 29.56±7.77 years, height: 177.81±2.17 cm, weight: 81.88±9.83 kg, CF experience: 14.56±7.17 months, 1RM thruster: 73.13±13.23 kg, 1RM clean and jerk: 78.25±15.72 kg), and beginner women (age: 29.06±7.84 years, height: 167.81±5.38 cm, weight: 66.88±9.13 kg, CF experience 15.94±5.91 months, 1RM thruster: 50.19±9.17 kg, 1RM clean and jerk: 54.63±8.63 kg).

3.3.2 Protocols

In study 3, participants went to their CF boxes twice to check their 1RM in the CJ and TH. Before this, they signed a consent form, and information like their height, weight, and CF experience was gathered. Before the main part of the session, participants did a five-minute warm-up on a bicycle ergometer (Concept2, Vermont, United States) at a low intensity, followed by a specific barbell warm-up for the exercises they were testing that day. Male athletes used a 20 kg Olympic barbell, while female athletes used a 15 kg barbell.

For the CJ session, participants performed two sets of a warm-up routine with one minute rest, consisting of five deadlifts, five pull cleans, five hang power cleans, ten front rack shoulder rotations, and three split jerks. On the day of the TH session, the warm-up consisted of five hang power cleans, ten front rack shoulder rotations, three push presses, three front squats, and five thrusts. After completing the warm-up, participants rested for three minutes before beginning the maximal strength test (Figure 9).

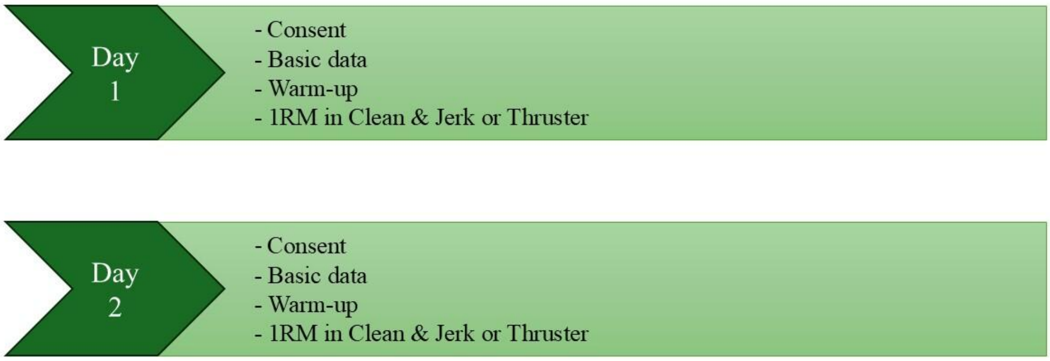


Figure 9. Scheme protocol of Study 3

The 1RM test used the Baechle and Earle protocol (Baechle & Earle, 2002) to find out the heaviest weight each person could lift in both exercises. Each test was done at the same time of day, with three days in between to give enough time to recover. Coaches watched the lifts to make sure the technique was correct and safe while noting the highest weight lifted. Participants also got verbal support during the 1RM tests (Belkhiria et al., 2018; Engel et al., 2019).

The rules for correctly performing the movements were as follows. The Clean and Jerk (CJ) had to start from the floor, include a clean catch in a half or full squat, and finish with a stable split jerk and straight elbows. Attempts were not valid if the elbows touched the knees during the clean, if the athlete used shoulder rebounds for the jerk, or if they moved the bar overhead before dropping it (Baker, 1994). For the Thruster (TH), a valid repetition had to start from the floor, include a full front squat, and smoothly transition into a push press without stopping, finishing with locked elbows (P. A. Bishop et al., 2008; Takano, 1987). Attempts were invalid if the elbows touched the knees during the squat or if the athlete moved overhead without fully extending their body before dropping the bar.

3.3.3 Statistical Analysis

First, the Shapiro-Wilk test was used to verify if the data followed a normal distribution. Second, a linear correlation analysis was conducted to examine the relationship between the 1RM in the CJ and maximum TH performance among all participants. Pearson´s correlation coefficients (r) were calculated for both variables with a 95% confidence interval (CI). The interpretation of the coefficient was based on Cohen´s modified criteria: minimal (<.10), small (.10–.29), moderate (.30–.49), large (.50–.69), very large (.70–.89), and huge (>.90). Following, a regression analysis was performed to assess if the amount of variation in CJ could explain the maximum load performed in TH. Moreover, multiple correlation and regression analyses were conducted, classifying participants based on (i) gender and (ii) experience level. To assess a more comprehensive approach, a machine learning-based statistical process, specifically a cluster analysis (CA), to identify different groups associated with weightlifting performance based on anthropometric characteristics. Four variables (TH performance, CJ performance, height and body weight) were included and analyzed. The clustering model was allowed to generate up to 10 clusters based on the relationships among these variables. An a priori alpha level of p≤.05 was established. All statistical tests were conducted using JASP software (v0.17.1.0).

3.4 Study 4, interventional approach: Chronic effects of individualised WODs

3.4.1 Participants

Twenty-five participants were enrolled in Study 4, of whom three withdrew during the intervention development. Consequently, 22 participants (12 males and 10 females) completed the intervention study. The sample had to meet specific inclusion criteria, which were verified with a questionnaire during an initial interview. To qualify, they needed to have attended CF lessons for at least 12 months, be able to perform a minimum of three pull-ups and five ring dips, and lift standardised weights in overhead movement (over 70 kg for men and 47.5 kg for women in the push jerk). Participants were excluded if they used performance-enhancing drugs, were pregnant, had cardiovascular, metabolic or respiratory disease conditions, or had an injury that could affect their health during the study.

During the intervention, participants avoided training outside the CF programme intervention and maintained their usual diet. They were divided into two groups based on the prescribed barbell load: (i) the group with Standardized Load (SL), which followed the benchmark WOD loads for men and women, and (ii) the group with Relativized Load (RL), which used a load calculated as a percentage of their 1RM in three barbell exercises. The groups obtained had the following characteristics, SL (age: 36.80±8.48 years, height: 171.56±10.38 cm, weight: 73.77±9.51 kg, CF experience: 82.99±36.78 months, BS/BW: 1.45±0.25 ratio), and RL (age: 39.25±7.36 years, height: 170.90±7.98 cm, weight: 73.76±12.96 kg, CF experience: 73.01±36.88 months, BS/BW: 1.42±0.24 ratio). Participants were grouped according to their strength ratio (maximum back squat weight divided by body weight) to minimize differences. In addition, both groups included an equal number of male and female participants to reduce potential gender-related differences.

3.4.2 Protocols

For Study 4, informed consent was obtained during the initial laboratory visit. Participants attended the laboratory on two occasions (at the beginning and end of the intervention) to collect descriptive data, including height, body weight, and CF experience, and also to measure their cardiopulmonary, metabolic, neuromuscular and subjective responses during a specific CF test called Tibana Test (TT) characteristic for evaluating the capacity of muscle endurance in athletes of this discipline (Tibana et al., 2021a). Moreover, following the laboratory tests, and with at least 72 hours of rest in between, study subjects performed the back squat (BS), the CJ, and the clean (C) 1RM measurements at the beginning, middle, and end of the program, following the protocol outlined by Baechle & Earle (2002).

The CF training program included 10 benchmark workouts, done in the second, third, and fourth weeks, and repeated in the sixth, seventh, and eighth weeks. In the fifth week, participants only did the 1RM tests to set the barbell weight for the RL group (Figure 10). Each CF session lasted one hour and had a general warm-up, preparation for the workout, the workout itself, and extra exercises.

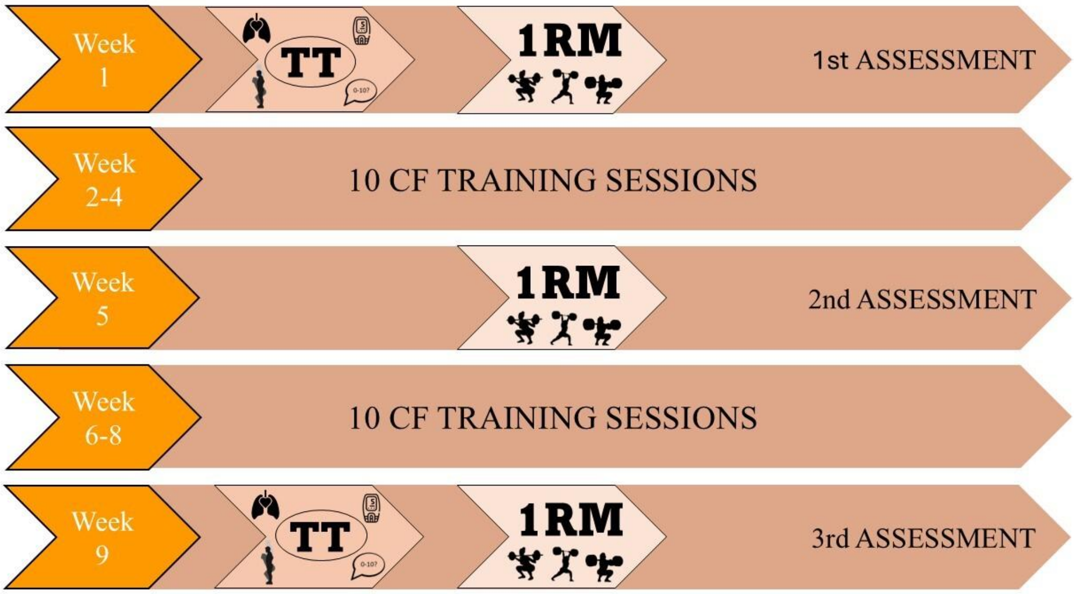


Figure 10. Scheme protocol of Study 4

Before and after the CF intervention, participants completed the TT in laboratory conditions. They were instructed not to engage in strenuous exercise the day before the test and to limit their intake of caffeine and alcohol. They were also advised to have a healthy meal and ensure they were drinking enough water three hours before the test. All athletes warmed up by rowing on an ergometer (Concept2, Vermont, United States) at an easy pace for three minutes before the TT. This process was followed by two sets of ten alternating lunges, twenty shoulder taps in the plank position, and ten seconds of isometric push-ups with elbows flexed. Following this, participants rowed for two minutes at a medium intensity. The testing procedure followed during the muscle endurance assessment of the TT included the measurements of the cardiorespiratory variables of VO_2 and HR, [La] level, neuromuscular fatigue in CMJ height, and the RPE of participants. Moreover, the repetitions performed by every subject were recorded in the different AMRAPs of this workout. Temporary points for the measures were before the TT started, after each AMRAP, including the fourth or final AMRAP, and five minutes after the finished measure at the end of the WOD.

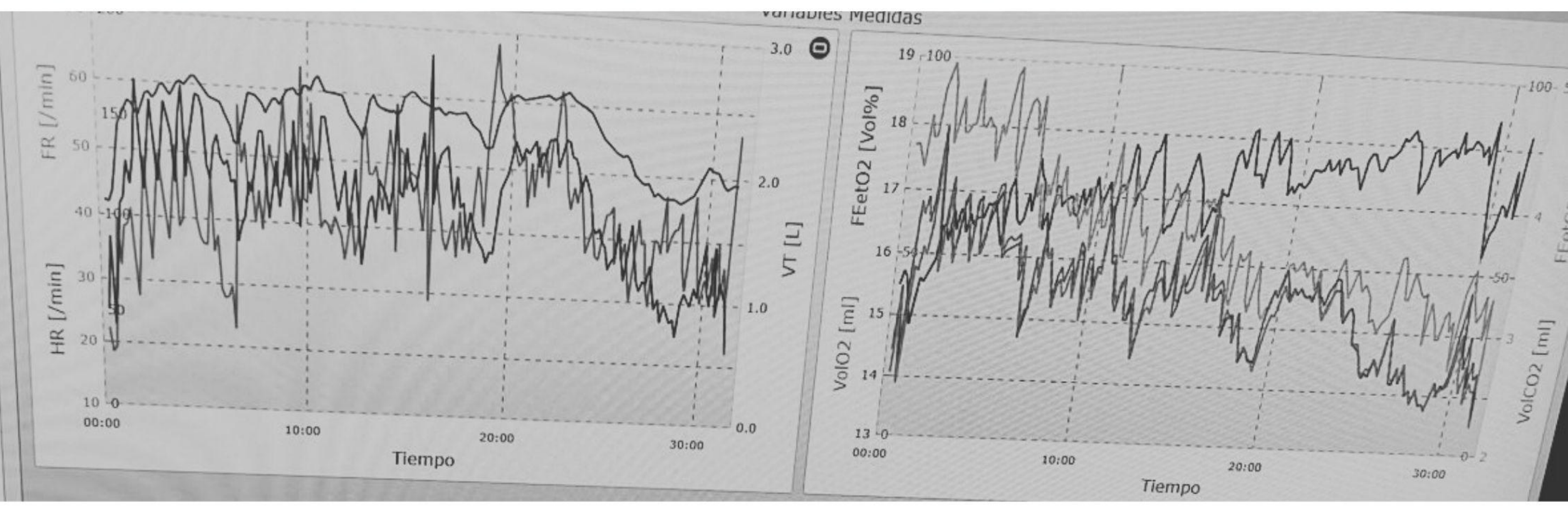
A modified version of the TT was performed to avoid incompatibility of exercises with the device to measure respiratory exchange. This version consisted of four AMRAPs to complete as many repetitions as possible within 4 minutes, followed by a 2-minute passive rest between every AMRAP. The TT workout was structured as follows: (AMRAP 1) five thrusters using two dumbbells (17.5 kg for males and 12.5 kg for females) and five box steps (50 cm for males and 40 cm for females) with dumbbells; (AMRAP 2) 10 dumbbell power cleans and 10 dumbbell rows; (AMRAP 3) 15 shoulders-to-overhead with dumbbells and 30 V sit-ups; and (AMRAP 4) 20 calories on a Concept II indoor rower (PM5, Vermont, USA) and 40 squat jumps.

3.4.3 Statistical Analysis

The variables derived from the four AMRAPs and the performance in total repetitions during TT, including VO_2peak, VO_2mean, HRpeak, HRmean, [La], CMJ, and RPE, were analyzed using a factorial ANOVA with two levels (pre and post) and two factors (SL and RL), except for the three-time points of 1RM in BS, CJ, and C (pre, mid, and post). Additionally, absolute and relative changes in [La] and

CMJ before and after the TT were calculated to assess pre-post variations. Before conducting ANOVA, data were tested for independence, homoscedasticity, and normality using the Durbin-Watson, Levene, and Shapiro-Wilk tests. All data are presented as means and standard deviations (M ± SD). The effect size (ES) for within-subjects comparisons was calculated using omega-squared (ω^2), which adjusts the variance explained according to the sample size. A post-hoc analysis was performed to evaluate the interaction between time points and each variable, applying Tukey's correction and interpreting Cohen's d effect size as small ($0.01 \leq \omega^2 < 0.06$), medium ($0.06 \leq \omega^2 < 0.14$), and large ($\omega^2 \geq 0.14$). To further explore changes in performance variables, including 1RM, CMJ, and TT repetitions, an individual athlete analysis was conducted using the Smallest Worthwhile Change (SWC) to provide a more accurate evaluation of performance adaptations in the SL and RL groups. A constant of 0.2 was used to establish the SWC threshold for trained individuals or athletes. Athletes were classified as responders or non-responders based on SWC, and the response rate was reported as a percentage for each group. Finally, differences in total and average training time and load between groups were compared using an independent t-test. Similar analyses were conducted for each WOD at different time points in the SL and RL conditions. Statistical significance was set at $p<0.05$. All statistical analyses and visualizations were performed using JASP (v0.18.3.0).

4. SUMMARY OF THE RESULTS



4. Summary of the results

4.1 Acute effect of three high-intensity functional workout designs

Performance in AMRAP varied among different skill levels. However, these differences went away when FT was adjusted for the total number of repetitions completed during the AMRAP. There were no differences in RPE between experienced and beginner athletes, but experienced participants found FT to be the most challenging and EMOM to be the least. Lactate levels rose in all three WOD formats for both groups, with much higher levels seen in FT compared to EMOM.

CMJ performance decreased after AMRAP in both groups and after FT in beginners, but not after EMOM. Also, HRmean and HRpeak showed no differences between groups or WODs, but HRV showed significant changes depending on workout and expertise, with notable decreases between AMRAP and FT in beginners.

4.2 Standardized vs Relative intensity in CrossFit

The strength levels of participants were closely linked to how many repetitions they could do in a standard AMRAP, and somewhat linked to their performance in the relativized WOD. The HS group did fewer repetitions in the relativized WOD, while the LS group had similar results across different WOD types. Participants in the HS group also felt more exertion after the standardized WOD compared to the relativized WOD, and LS participants felt more exertion than the HS group only during the standardized AMRAP.

CMJ performance decreased in the HS group after both WODs, whereas the LS group decreased only after the relativized AMRAP. Blood lactate concentration increased in all participants after both WODs, with no differences between WODs or groups. HRpeak values were consistently high for all participants, exceeding 90% without significant differences between WODs. However, the relativized WOD was more demanding than the standardized WOD for LS participants.

4.3 Prediction of Thruster maximum load with Clean and Jerk 1RM

Strong relationships were found between 1RM in TH and CJ performance, with different patterns seen when looking at participants by gender and CF experience. The coefficient of determination was high for all participants and in specific models, but a bit lower for beginner women.

Predictive equations were created using the constants from the regression model (Figure 11). A clustering analysis found four groups based on the connections between 1RM in TH, 1RM in CJ, height, and body weight.

EXPERIENCED MEN : (TH=0.81*CJ+9.98)

EXPERIENCED WOMEN : (TH=0.63*CJ+17.39)

BEGINNERS MEN : (TH=O.80*CJ+10.23)

BEGINNERS WOMEN : (TH=0.96*CJ+(-2.21)

Figure 11. Predictive equations for Thruster (TH) through the maximum repetition in Clean and Jerk (CJ)

4.4 Effects of a CrossFit intervention with individualised load adjustments compared to benchmark *Rx* weights

Only the RL group showed significant improvement in total performance in the TT after the CF intervention, while the SL group showed a non-significant trend. Both groups improved in the four AMRAPs, but no significant interaction effects were found. The RL group increased their 1RM in BS and C, while the SL group showed no significant changes. Neither group improved in CJ performance or CMJ height, and both groups decreased their CMJ height post-TT.

No significant changes were observed in cardiopulmonary variables or lactate levels. Perceived effort was similar between groups, though the RL group had lower initial RPE and higher final RPE. Training load analysis revealed no significant differences, but the SL group spent more time training and lifted more load (repetitions x kg) in specific WODs.

In the end, 70% of SL participants and more than 83% of RL participants showed performance improvements, particularly in the number of responders for 1RM and CMJ among RL participants. Also, all athletes who did the CF intervention with adjusted weights finished the study, but not all SL participants completed the intervention (Figure 12).

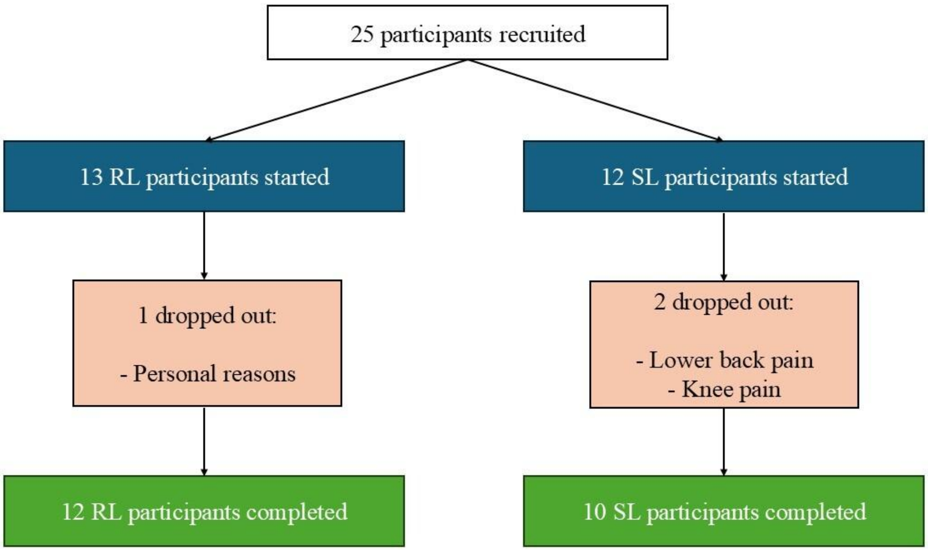


Figure 12. Participant flow over the course of Study 5

5. GENERAL DISCUSSION

5. Summary of the discussions

5.1 Acute effect of three high-intensity functional workouts

The results back up Hypothesis 1. The study showed that FT workouts caused the strongest immediate physical and mental reactions, like higher lactate levels and perceived exertion, compared to AMRAP and EMOM, which agrees with earlier research by Timón et al. (2019) that found higher lactate levels in FT than in AMRAP. EMOM workouts had the lowest lactate levels and feelings of fatigue because of the rest periods, especially for experienced participants (Maté-Muñoz et al., 2017), who found that skilled athletes completed EMOM rounds quicker and had more time to recover between sets. So, the data indicate that FT creates the highest immediate physical demand, followed by AMRAP and EMOM, showing that the type of workout matters more than the amount or weight used in affecting physical and mental responses.

For Hypothesis 2, we found contradictory results. Participants of the EG demonstrated better performance in AMRAP despite using the same relative load and training volume as IG participants. This finding supports the observations of Butcher et al. (2015), who also reported that experienced athletes completed more repetitions in AMRAP workouts. This suggests that training experience may enhance performance, specifically in AMRAP structures. However, no significant differences were found between experienced and beginner participants in FT and EMOM workouts, which contrasts with the findings of de Sousa-Neto et al. (Sousa Neto et al., 2022), who observed that FT training emphasizes differences between experienced and inexperienced athletes due to its requirement to complete repetitions as quickly as possible. This indicates that experience may not consistently affect physiological and psychological responses across all workout distributions.

5.2 Standardized vs Relative intensity in CrossFit

Hypothesis 3 was confirmed by this study's results, which showed that when individuals with different levels of strength completed a WOD with their relativised load, repetitions and RPE were homogenised independently of their level. Our results are in line with the evidence research, suggesting that individualising training parameters, such as intensity, can optimise the dose and effects of training, regardless of participants' strength levels (Coackley & Passfield, 2017; Schwingshandl et al., 1999; Zabaloy et al., 2020). However, specific literature on CF individualisation of training suffers from a lack of evidence before our study presented in this thesis.

Regarding Hypothesis 4, it was confirmed because both the HS and LS groups experienced a similar decrease in CMJ height and an increase in blood lactate concentration after both the relativised intensity AMRAP and the standardised WOD, indicating that the physiological response was comparable regardless of the participants' strength level. On the one hand, these results are in line with other authors, who found a decrease in the CMJ performance immediately after finishing similar WODs to that in our study with experienced and inexperienced participants, supporting the idea that acute fatigue responses are consistent across different strength levels (Maia et al., 2019; Maté-Muñoz et al., 2018). On the other hand, several authors (Shaw et al., 2015; Tibana et al., 2016) also reported values of [La] around 10 mmol/L after CF training, assuming metabolic fatigue was induced from this high-intensity training modality regardless of the strength level of the participants.

5.3 Prediction of Thruster maximum load with Clean and Jerk 1RM

Our Hypothesis 5 was confirmed because the results showed a strong relationship between the CJ 1RM and the maximum load lifted in the TH movement. This result supports the idea that these two movements have a significant association derived from similar movement patterns. Moreover, the gender and experience in CF training of participants reinforce the hypothesis that the strength of the correlation varies based on these factors. In some scientific reports, we have found relationships between movements such as the back squat and the clean and jerk or between different overhead movements, highlighting the importance of hip and knee extensor strength, which is fundamental to weightlifting performance, and demonstrating the high correlation in maximum performance between different movements (Lucero et al., 2019; Shetty, 1990; Soriano et al., 2022).

Hypothesis 6 was partially confirmed as the results showed a higher coefficient of determination for men and experienced women, indicating that the prediction and accuracy for TH performance based on 1RM CJ was greater in participants with more than two years of CF training. Nevertheless, the lower level in the model regression observed in beginner women underscores the influence of gender, beyond the effect of CF experience, in modulating the observed associations. This finding aligns with the idea that technical mastery plays a significant role in consistency for athletes with lower absolute strength levels (Soriano et al., 2022). Furthermore, the stronger correlation in men may be explained by higher absolute strength values, which contribute to greater consistency in 1RM performance, and the idea is supported by other authors that weightlifting performance shows higher accuracy in weightlifting performance among experienced lifters compared to inexperienced ones (Lucero et al., 2019).

5.4 Effects of a CrossFit intervention with individualised load adjustments compared to benchmark Rx weights

Our Hypothesis 7 was partially refused because, although the RL group showed a significant improvement in performance during TT, the interaction between group and time did not show significant differences with the improvement of the SL group. Furthermore, the RL group increased their 1RM in the BS and the C, showed significant improvements in these strength measures following the CF intervention. However, the SL group did not show significant changes in 1RM for these variables, underscoring a difference in strength development between the two groups. Although no studies have specifically examined the individualization of barbell load, previous research has reported benefits from prescribing intensity based on variables such as HRV or HR. These studies have found improvements in overall performance during WODs and increases in maximum strength in relativised groups, even when these groups trained with a lower total training load compared to those following standard loads or fixed programs (Deblauw et al., 2021; Held et al., 2024).

Lastly, Hypothesis 8 was supported because no significant differences were found in VO_2, HR, CMJ, and [La] at the end of the intervention within or between groups in the TT. Although both groups exhibited high acute neuromuscular and physiological responses before and after the test, an absence of differential changes would not result in comparable efficiency after the CF intervention between RL and SL. Other studies with experienced CF participants did not find significant differences in physiology parameters during a maximal test on a stationary bike after a CF intervention Therefore, since both studies the participants improved their performance test results, and no differences were found in VO_2max, we can confirm that in both cases they had more efficient responses in HR and VO2 parameters (Held et al., 2024).

6. CONCLUSIONS AND PRACTICAL APPLICATIONS

6. Conclusions and practical applications

6.1. General conclusions

This doctoral thesis is structured into four studies. Studies 1 and 2 explore the differences in performance, physiological, neuromuscular and subjective responses of CF participants when WODs are structured in different formats (AMRAP, FT or EMOM) or when the barbell weight is individualized using their 1RM. Study 3 establishes a prediction equation to know the 1RM of the most repeated barbell movement in CF WODs (TH), knowing the repetition maximum in CJ. Study 4 examines the adaptations and performance changes that may occur in experienced CF athletes when implementing a training intervention that adjusts WOD loads based on their 1RM.

The main conclusions of this thesis are:

Study 1

1) FT workout distribution leads to the strongest immediate physical reactions, like higher [La] and RPE levels, when compared to AMRAP and EMOM. This shows that how a workout is structured might be just as important as the amount of exercise and weight used, since it affects both physical and mental responses.

2) Training experience improves performance, especially in AMRAP workouts, where seasoned athletes usually do more repetitions with the same weight. However, when we adjusted the training load based on their total AMRAP score, there were no major differences between experienced and beginner athletes in FT and EMOM workouts. This indicates that the structure of the workout is an important factor, along with the intensity or volume.

Study 2

3) Individualising load intensity in WODs leads to a higher HRmean in weaker athletes compared to using standardised loads, indicating a greater cardiovascular demand when adjusting loads based on individual strength levels.

4) Stronger athletes tend to perform fewer repetitions, achieve a lower jump height in the CMJ test, and report higher RPE when using relativized loads compared to standardized loads, highlighting the impact of load adjustment on performance and effort perception.

Study 3

5) The CJ movement is closely linked to the TH, as it is the most commonly performed movement in CF workouts. Additionally, when looking at participants by gender and CF training experience, this strong link shows that TH performance is still closely related to CJ, regardless of these factors.

6) The high coefficients of determination in most models (experienced men, beginner men, experienced women, and beginner women) show that the regression equations are good at predicting TH performance based on CJ results, even though the model for beginner women had a slightly lower but still strong value.

Study 4

7) The use of individualized barbell loads in strength movements led to improvements in CF performance similar to following a CF program performed WODs with Rx loads, with the difference of a significant improvement in maximum strength. These study results highlight the effectiveness of adjusting loads to the capabilities of each athlete.

8) The absence of significant differences in VO_2, HR, CMJ and [La] between the individualized load and standardized load groups before and after intervention suggests similar physiological adaptations. This fact, in combination with both groups' improvement in the TT, performing more repetitions, indicates a greater efficiency in their cardiovascular and muscular system.

This dissertation's findings demonstrate that CF training is a high-intensity multimodal training method that demands individualization to optimize performance and physiological adaptations, given the diverse characteristics and responses of participants worldwide. Study 1 showed that the structure of FT workouts, rather than volume or load, elicits the greatest acute physiological responses compared with FT and EMOM. Moreover, EMOM workouts resulted in less neuromuscular fatigue or [La] values due to rest time intervals, especially for experienced CF athletes. In study 2, the use of relative loads for barbell weight depending on their 1RM of the participants, elicits the desired high-intensity acute response targeted by CF training during the WOD section of the sessions. Moreover, complementing the latest study and relativizing training loads, study 3 showed that CJ movement strongly predicts TH performance across gender and experience levels. Finally, study 4 showed that individualized barbell loads enhance maximum strength without compromising cardiovascular or muscular adaptations, achieving similar improvements in CF performance as Rx loads established by CF benchmarks.

6.2. Conclusiones generales

Estudio 1

1) El entrenamiento FT produce las mayores respuestas fisiológicas agudas, como niveles elevados de [La] y RPE, en comparación con AMRAP y EMOM. Esto resalta que la estructura del entrenamiento es un factor clave a considerar por su influencia en las respuestas fisiológicas y psicológicas derivadas de los WODs de CF.

2) La experiencia de entrenamiento en CF mejora el rendimiento, especialmente en los AMRAP. En estos, los atletas experimentados tienden a completar más repeticiones con la misma carga relativa. Sin embargo, no se encontraron diferencias significativas entre atletas experimentados y principiantes en los entrenamientos FT y EMOM cuando se emparejó la carga de entrenamiento según su puntuación total en AMRAP. Estos datos sugieren que la estructura del WOD es una variable clave, al igual que la intensidad o el volumen.

Estudio 2

3) La individualización de la intensidad de carga en los WODs conduce a una FC media más alta en los atletas menos fuertes en comparación con el uso de cargas estandarizadas, lo que indica una mayor demanda cardiovascular al ajustar las cargas según los niveles individuales de fuerza.

4) Los atletas más fuertes tienden a realizar menos repeticiones, lograr una menor altura en el salto CMJ y reportar un mayor RPE al usar cargas relativizadas en comparación con cargas estandarizadas, lo que resalta el impacto del ajuste de la carga en el rendimiento y la percepción del esfuerzo, otorgando al entrenamiento un estímulo más vinculado a la alta intensidad de CF.

Estudio 3

5) El movimiento CJ tiene una fuerte correlación con el TH, siendo este el movimiento más repetido en los entrenamientos de CF. Además, al agrupar a los participantes según género y experiencia en CF, esta alta correlación sigue indicando que el rendimiento en TH tiene una fuerte relación con el rendimiento en CJ independientemente de estas variables.

6) Los altos coeficientes de determinación en la mayoría de los modelos (hombres experimentados, hombres principiantes, mujeres experimentadas y mujeres principiantes) confirman la precisión predictiva de las ecuaciones de regresión para estimar el rendimiento en TH en función de los resultados en CJ, aunque el modelo para mujeres principiantes mostró un valor ligeramente más bajo, pero aún muy altas.

Estudio 4

7) El uso de cargas individualizadas en los movimientos de fuerza condujo a mejoras en el rendimiento y en la fuerza máxima, similar a seguir un programa de CF realizado con WODs con cargas Rx, con la diferencia de una mejora significativa en la fuerza máxima. Estos resultados del estudio destacan la efectividad de ajustar las cargas a las capacidades de cada atleta.

8) La ausencia de diferencias significativas en VO_2, frecuencia cardíaca (FC), CMJ y [La] entre los grupos de carga individualizada y carga estandarizada antes y después de la intervención sugiere adaptaciones fisiológicas similares. Este hecho, combinado con la mejora de ambos grupos en el TT, realizando más repeticiones, indica una mayor eficiencia en su sistema cardiovascular y muscular.

Los hallazgos de esta tesis doctoral demuestran que el entrenamiento en CF es un método multimodal de alta intensidad que requiere individualización para optimizar el rendimiento y las adaptaciones fisiológicas, dada la diversidad de características y respuestas de los participantes a nivel mundial. El estudio 1 revela que la estructura de los entrenamientos FT, más que el volumen o la carga, genera las mayores respuestas fisiológicas agudas en comparación con AMRAP y EMOM, siendo este último el que provoca menor fatiga neuromuscular y menores niveles de [La] gracias a los intervalos de descanso, especialmente en atletas de CF experimentados. El estudio 2 demuestra que el uso de cargas relativas en los levantamientos con barra, ajustadas en función del 1RM de cada participante, permite alcanzar la respuesta aguda de alta intensidad que busca el CF durante la sección de WOD. Además, el estudio 3 confirma que el movimiento CJ predice de manera sólida el rendimiento en TH, independientemente del género y nivel de experiencia, reforzando la importancia de relativizar las cargas de entrenamiento. Finalmente, el estudio 4, muestra que el uso de cargas individualizadas en barra mejora la fuerza máxima sin comprometer las adaptaciones cardiovasculares o musculares, logrando mejoras en el rendimiento en CF similares a las obtenidas con las cargas *Rx* establecidas en los *benchmarks* de CF.

6.3. Limitations and future directions

The studies included in this doctoral thesis are not free of limitations. At the same time, these limitations can contribute to establishing new research perspectives in the strength and conditioning field. The limitations and future research objectives are outlined as follows:

1) In Study 1, the workouts were homogenized based on AMRAP performance, which created a slight imbalance in the execution time between AMRAP and FT because the second workout was completed faster than the first. Future studies should explore the effects of homogenizing workouts based on FT or EMOM to assess potential differences in physiological and performance responses.

2) In Study 1, the EMOM structure may have influenced the athlete's performance, as more experienced athletes could perform additional rounds. This scenario could have resulted in unequal workloads among participants, affecting the comparability of the results.

3) In Study 1, the optimal approach would have been to conduct a longitudinal intervention study in which three training groups, each focusing on a different training modality (AMRAP, FT or EMOM), could have been evaluated. However, due to the athletes' competition calendar and their preparation for peak performance, only a descriptive cross-sectional study could be conducted.

4) In Study 2, the authors relied on theoretical HRmax instead of doing a test to find out the participants' real HRmax, which might have impacted how accurately they assessed the cardiovascular response.

5) In Study 2, the push press test was employed to classify the bodyweight-1RM ratio instead of the more commonly used back squat 1RM test. This could have influenced the classification of strength levels and the interpretation of the load-relative responses.

6) In Study 3, the variability in CF athletes' height, body weight, and relative strength may have influenced the load lifted and the outcomes in the analyzed exercises. Future studies should control for these anthropometric variables to enhance the consistency of the findings.

7) In Study 4, the short length of the intervention might have made it hard to see the long-term changes that usually come from training over a longer time. However, this short duration matches what happens in CF training, where brief interventions are often needed because of athletes' training schedules.

8) Study 4 didn't have a control group, making it hard to say that the changes seen were only due to the intervention. Adding a control group is difficult in CF studies because it would mean participants have to stop their usual CF routines, which is often not practical.

9) In Study 4, future research should investigate the potential for enhancing individualization by monitoring heart rate zones to adjust training loads; similarly, establishing biomechanical guidelines for prescribing gymnastic movements based on individual characteristics could improve the precision of training programs.

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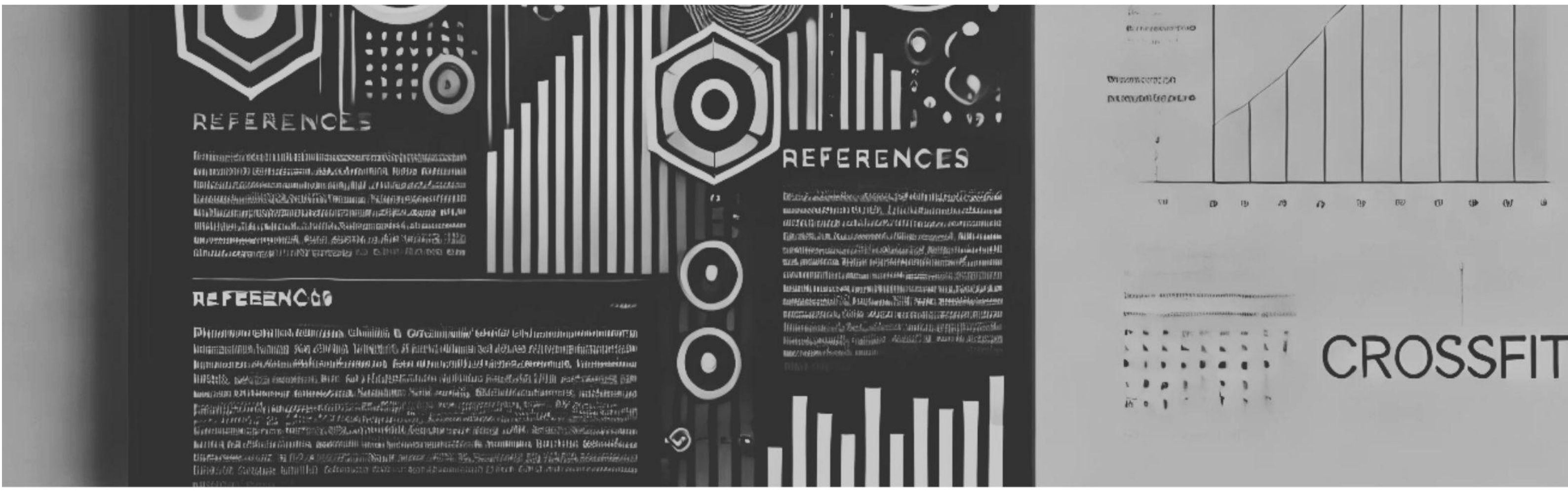

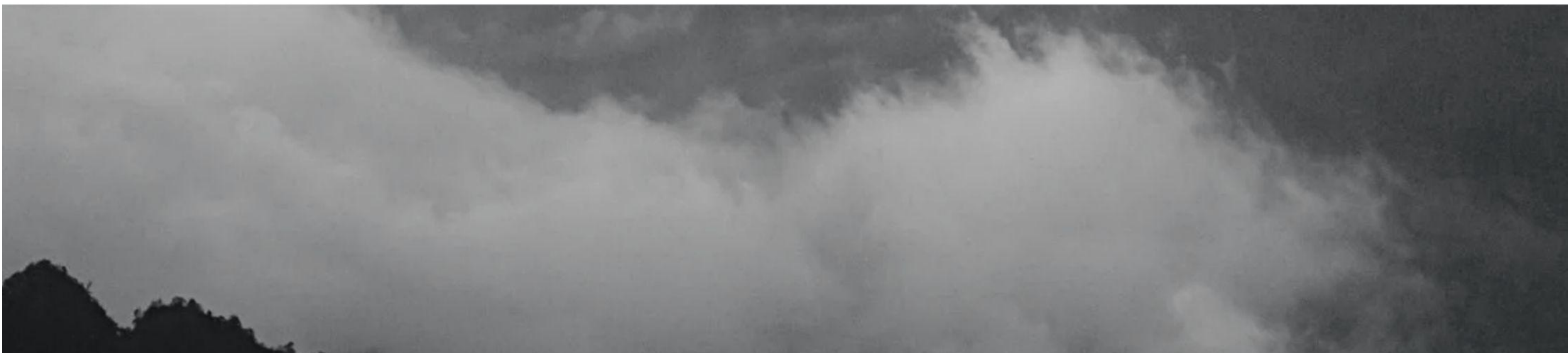

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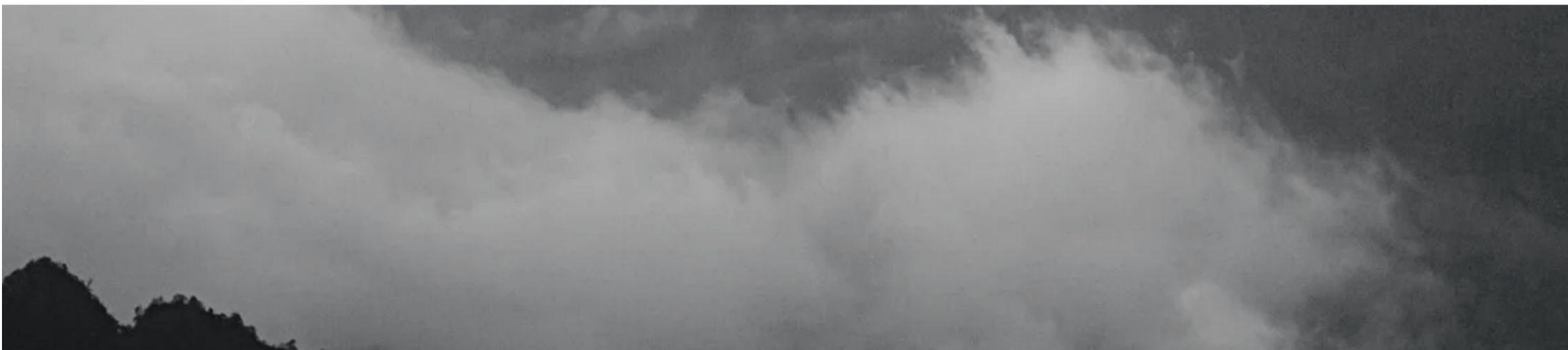
8. APPENDICES



APPENDIX 1.

Note: This study was published.

8.1 STUDY 1: Oliver-López A, García-Valverde A, Sabido R. 2025. Acute effect of three Functional Fitness Training workout designs with equalized load on inexperienced and experienced athletes. *PeerJ 13*: e19265. http://doi.org/10.7717/peerj.19265

8. Chapter 8: Appendices. Appendix 1

Study 1: Acute effect of three high-intensity Functional Fitness Training designs with equalized load on inexperienced and experienced athletes

ABSTRACT

Background: In the realm of Functional Fitness Training (FFT), three common circuits—As Many Repetitions or Round As Possible (AMRAP), FOR TIME (FT), and Every Minute on a Minute (EMOM) —are prevalent. We aimed to elucidate the immediate impacts on athletes, considering the experience, when performing three workout modalities with matched training loads.

Methods: Twenty-five healthy men and women, with at least three months of experience in FFT, were allocated into the Inexperienced Group (IG) and Experienced Group (EG). The cut point for allocating participants in each group was set at 24 months. All of them participated in three workouts (AMRAP, FOR TIME and EMOM) with three days of rest. A double comparison was performed between level of experience (IG and EG) and among kinds of training in rating of perceived exertion (RPE), lactate concentration (Lac), countermovement jump (CMJ), heart rate (HR) and heart rate variability (HRV) using ANOVA and post-hoc Bonferroni tests.

Results: Sex was initially analyzed but had no influence, leading to combined group analyses. The workout type significantly impacted performance, with AMRAP showing differences between expertise levels (ES = 0.81, $p = .044$). RPE varied by workout type ($F(2,46) = 11.003$; $p < .001$), with EG reporting FT as the most and EMOM as the least demanding. Lactate levels increased across all workouts, with FT showing the highest and EMOM the lowest levels ($ES = 1.05$, $p < .001$). CMJ performance declined post-AMRAP and FT in both groups, but not after EMOM. No expertise-level differences were found in HRmean or HRmax, but HRV changes were influenced by workout type ($F(2,46) = 7.381$; $p < .01$) and expertise ($F(1,23) = 4.657$; $p = .034$), with significant decreases in HRV after AMRAP and FT for IG.

Conclusion: The study demonstrates that FT produced greater Lac and RPE as compared to an AMRAP, whereas EMOM generated less neuromuscular fatigue and Lac, particularly in EG. These results underscore the importance of individualizing workout selection to expertise level to optimize performance. Future research should explore longitudinal adaptation to different workout types across diverse populations.

Key words: High-intensity resistance training, physiological responses, blood lactate, fatigue, functional performance.

INTRODUCTION

Functional Fitness Training (FFT) is an exercise modality that emphasizes multi-joint movements which elicit greater muscle recruitment and can be adapted to any fitness level (Feito et al., 2018). FFT design which combines movements from different disciplines, such as weightlifting, gymnastics and cardiovascular exercises component (Tibana et al., 2018). In general, FFT sessions can be divided into three parts: warm-up, strength or skill and workout. The workout incorporates both aerobic and anaerobic training styles in intervals to improve aerobic fitness and body composition (Dehghanzadeh Suraki et al., 2021) and its design varies from day to day but typically includes a mixture of high-intensity exercises of 5 - 20 mins. and many repetitions requiring high muscular endurance and strength (Drum et al., 2017; Tibana et al., 2021). These characteristics can lead to excessive training sessions, not only for Inexperienced, but also for experienced athletes (Weisenthal et al., 2014).

Frequently, many FFT trainers prescribe workouts whose structure is based on a given time frame to complete all exercises (As Many Rounds and Repetitions As Possible, AMRAP) or prompt athletes to do the workout as fast as possible (For Time, FT), thus both instructions often focus on the overall timing of the workout (Mullins, 2015). Conversely, Every Minute On a Minute (EMOM), which is considered as interval training, is characterised by its design in time windows during which athletes are asked to keep a pace per round, although they might reach a higher recovery time if they perform faster (Da Silva-Grigoletto et al., 2020).

However, this assumption of workout structures raises some concerns about the efficiency and effort self-regulation among athletes depending on their performance levels, since the workout intra-schedule would make it complicated to estimate optimal intensity (Mangine & Seay, 2022). In this sense, for the same number of repetitions, the time under tension in lower-level athletes will be greater, with the consequent repercussions on fatigue, thus conditioning the possibility to maintain the execution speed during successive repetitions (Mazzetti et al., 2007).

Consequently, these athletes might show greater responses as a result of a higher demand in physiological variables like lactate concentration, heart rate and variability, which are characteristic responses to this type of training, while neuromuscular fatigue might be shown as a decrease in jump ability. In connection with the self-regulation effort that each kind of workout allows, different responses and coping strategies have been noted, so the rate of perceived effort (RPE) might differ depending on the athlete's experience and kind of workout.

In AMRAP, athletes perform the maximum repetitions, and they are the ones who split their breaks during training. This modality offers all athletes equal work time, but the intensity and volume of load will depend on each one of them. According to Bellar et al. (2015), AMRAP is an interesting choice should the athlete be an inexperienced. This is so due to the fact that participants, regardless of their prior athletic background, exhibit a substantial physiological and cardiovascular response in terms of both aerobic fitness and anaerobic power during this workout (Dias et al., 2022; Meier et al., 2022).

However, in FT, athletes have to perform the set of repetitions in the shortest time, thus athletes with a higher relative strength will have a lower loss of velocity in repetitions and higher performance, delaying the fatigue effects (Butcher et al., 2015). FT training will emphasise the differences between experienced and inexperienced athletes, as here everyone will perform the same number of repetitions. Responses in neuromuscular fatigue are remarkable in this type of distribution (de Sousa-Neto et al., 2022).

Lastly, in EMOM, inexperienced athletes will have a higher relative load at the set intensity, and they will have less rest time to start the next round of the minute, which will result in greater fatigue levels during the workout. The work-rest ratio within the minute will be the key element to differentiate training intensity, due to the fact that recovery periods are essential to avoid muscle fatigue and injury, especially in participants that are only starting FFT (Maté-Muñoz et al., 2018).

Despite the fact that many studies have measured acute responses to different types of workouts, only a few have addressed the specific differences that may exist among athletes' responses as a function of the workout distribution with homogenized loads (Toledo et al., 2021) and there are none comparing AMRAP and FT with the EMOM distribution (Forte et al., 2022; Timón et al., 2019), which is the novelty addressed in this study. Therefore, knowledge of the potential difference between kinds of workouts might provide fitness coaches a better understanding of how to optimize training programs for athletes and select the most appropriate workout type based on the experience level and goals.

Thus, in the present study we aimed to describe specific cardiovascular, metabolic and perceived exertion responses that experienced and inexperienced participants in FFT developed towards the three types of training, with a similar volume and relative load but organized in different workout modalities according to experience level. We hypothesize that the FT workout design could produce higher physiological and psychological responses than structures such as AMRAP or EMOM in both experienced and inexperienced participants, regardless of the volume and total load of the training.

MATERIALS & METHODS

Participants

Twenty-five people (15 males and 10 females) who practiced HIFTFFT and had at least three months of experience took part in this study. The most experienced participants had up to 36 months of experience (Table 1). We only excluded those participants who had: (i) few than three months of experience in HIFTFFT; (ii) metabolic disorders, cardiovascular diseases or musculoskeletal injuries that could affect testing or training (e.g. muscle strains, contusions, etc); (iii) taken drugs or supplements that would affect the measurements (e.g. benzodiazepine or caffeine); (iv) not rested for at least 72 hours before the sessions. In addition, we assigned participants with experience in HIFTFFT higher than 24 months to the Experienced Group (EG). Otherwise, we assigned those with an experience lower than 24 months in this discipline to the Inexperienced Group (IG) for comparison to previous studies (Mangine & Seay, 2022; Menargues-Ramírez et al., 2022). Prior to the enrolment, we informed all participants about the protocol, potential risks and they signed an informed written consent. We developed this study following the guidelines of the Declaration of Helsinki and conducted it in accordance to the research committee of the Miguel Hernández University (Ethics Committee ID: 230210121042).

Table 1. Athletes' descriptive characteristics (mean ± standard deviation) according to strength level.

	IG (W) = 7 / (M) = 5	EG (W) = 3 / (M) = 10
Age (years)	W: 29.1 ± 6.1 M: 28.6 ± 5.1	W: 36.7 ± 9.8* M: 39.1 ± 6.9*
Height (cm)	W: 164.1 ± 7.3 M: 175.9 ± 12.2	W: 160.5 ± 3.3* M: 174.5 ± 5.7
Body weight (kg)	W: 67.6 ± 8.6 M: 77.6 ± 20.1	W: 59.2 ± 5.5* M: 78.6 ± 8.4
CF experience (months)	W: 16 ± 8.6 M: 20.2 ± 4.3	W: 82.3 ± 52.2* M: 66.1 ± 30.7*
Ratio[1]	W: 0.69 ± 0.9 M: 0.97 ± 0.1	W: 0.97 ± 0.2* M: 1.07 ± 0.1*

Note: IG = Beginner Group; EG = Experienced group; W = Women; M = Men
[1] maximal weight lifted in push press divided by bodyweight; * $p < .05$

Study design

We designed an observational study. Participants performed three kinds of workouts and rested for 72 hours between workout days (Bishop et al., 2008). Previously, we had assessed participants with a one-rep max on the push press movement which was performed according to NSCA guidelines (Haff & Triplett, 2015) to relativize load intensity in weightlifting movements. The barbell weight selected was 75% of 1RM Push Press as this is a limiting exercise in terms of kilograms lifted when compared to Clean & Jerk (Buitrago & Jianping, 2018; Lake et al., 2014). Before each workout, participants performed a warm-up of five minutes of jogging, three series of 10 repetitions of joint mobility (push up to bear, lunge with thoracic mobility and pull-downs using a bungee cord) and two series of progressive intensity including the movements in the workout (Table 2). Following this, they performed one of the designed workouts. In the first workout-session, participants carried out an AMRAP lasting 12 minutes. Individual performance (considered as repetitions) in this workout was used to set up the For Time and EMOM modalities. In this sense, AMRAP volume and intensity were reproduced in For Time and EMOM so that each participant performed the same individual load in every workout. We encouraged participants to perform as fast as possible the For Time workout which was set with the same volume as they used in AMRAP. To optimize the EMOM structure, we organized the exercises and distributed the total individual volume equally across each minute while preserving the total volume achieved in the AMRAP. The specific distribution was as follows: (i) 1st minute for weightlifting movements only; (ii) 2nd minute for gymnastic movements only; (iii) 3rd minute for running only (Figure 1). All participants completed the EMOM according to the distribution given.

Table 2. Descriptive of volume and intensity for each exercise in every WOD.

Exercise	AMRAP (12')		FOR TIME (max. 12')		EMOM	
	Volume	Intensity	Volume	Intensity	Volume	Intensity
Power clean	5 rep	75% 1RM	5 rep	75% 1RM	5 rep	75% 1RM
Push press	3 rep	75% 1RM	3 rep	75% 1RM	3 rep	75% 1RM
Pull up	5 rep	Body weight	5 rep	Body weight	5 rep	Body weight
Push up	8 rep	Body weight	8 rep	Body weight	8 rep	Body weight
Air Squat	10 rep	Body weight	10 rep	Body weight	10 rep	Body weight
Run	150 m	Free	150 m	Free	150 m	Free

Note: "AMRAP": maximum number of repetitions in 12 minutes; "FOR TIME": less time in complete the number of repetitions of the last week AMRAP with a Time Cap of 12´; "EMOM": as many minute rounds as repetitions in the AMRAP

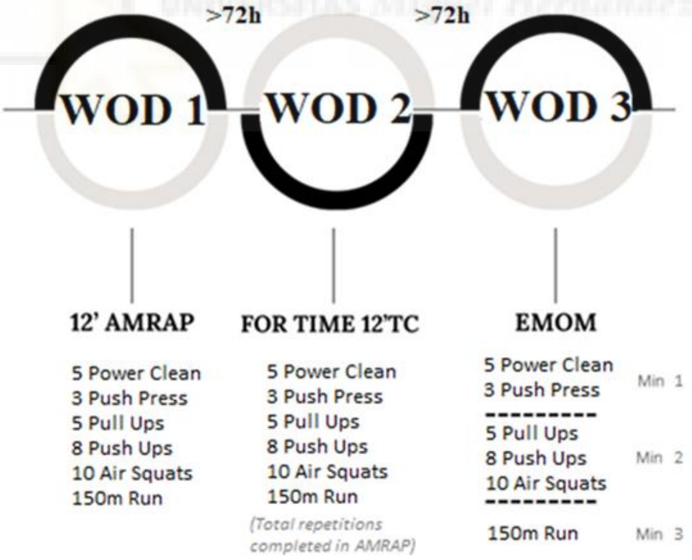


Figure 1. Study design and timeline used to evaluate the acute effects on athletes' performance. [2] Power Clean and Push Press (75% 1RM in Push Press movement)

To increase extrinsic motivation, we verbally encouraged all participants and matched them to a similarly performing opponent (Partridge et al., 2014). We recorded performance (repetitions in AMRAP, time to finish FT and rounds in EMOM), rating of perceived effort, change in jump ability, blood lactate, heart rate and heart rate variability before and after each workout (Figure 2).

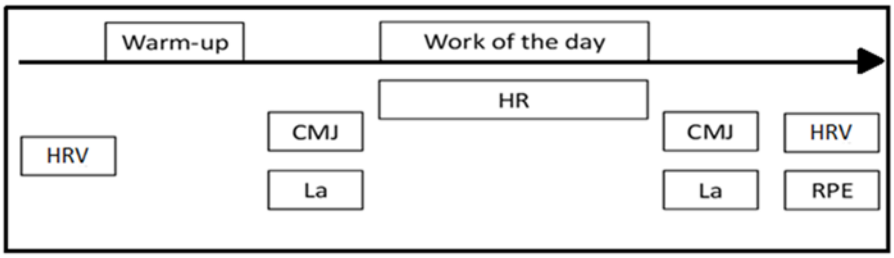


Figure 2. Session design. CMJ = countermovement jump, La+ = Lacticaemia, HR = heart rate, HRV = heart rate variability, RPE = ratio of perceived effort.

Procedures

Performance

We performed each workout under the supervision of two qualified coaches to ensure that we met movement and workout standards. In the AMRAP, the judges recorded the athletes' total number of valid repetitions. In FT, judges decided on the number of repetitions that athletes had to perform and when completed, the judges stopped the clock to record the athletes' best time. Finally, for EMOM, judges made sure that athletes performed the number of repetitions of each minute with the correct movements and counted down (three, two, one, go) to warn participants that the next minute was starting.

Perceived effort

We obtained the rating of perceived exertion values (RPE) by using the Borg category scale (CR-10) (Foster et al., 2001). We had made all athletes familiar with this scale for rating perceived exertion before the commencement of the study. CR-10 consists of a scale for exercise intensity ranging between "rest" (0) and "maximal" (10). We asked participants the following question: "How hard do you feel the workout was?", 30 minutes following the conclusion of the workouts to ensure that the perceived effort referred to the whole workout rather than the most recent exercise intensity (Day et al., 2004).

Peripheral blood lactate concentration

We determined blood lactate concentration (Lac) by an average of test strips and a portable analyzer (Lactate Scout Plus, Biolaster, Gipuzkoa, Spain) in peripheral blood samples taken from the left earlobe, one-minute after warm-up (basal) and one minute and a half upon workout completion following the CMJ (Tanner et al., 2010). Prior to extracting the sample, we cleaned the skin with chlorhexidine. We discarded for analysis the two-first blood drops, and the third drop was used.

Jump Ability

Jump height was assessed by Globus mat (Ergo Tester, Codognè, Italy) at the end of the warm-up and immediately after completing the workout. All participants performed six progressive CMJs after the warm-up and were then asked to do three CMJs as high as possible with one minute of rest. They were required to keep their hands on their waist during all the test and to land with straight knees. Rebound-on landing was allowed through flexo-extension of ankles. The first contact with the mat stopped the stopwatch and the best attempt was used for analysis.

Heart Rate

Participants wore a chest band during workouts placed on the xiphoid area of the sternum with a portable device (Polar H10, Kempele, Finland), to record the heart rate (HR). We used a smartphone app (Polar Team, Kempele, Finland) to monitor several athletes at the same time. At the end of every workout, we collected the HR average (HRmean) and HR maximum (HRmax).

Heart Rate Variability

Prior to the warm-up and after each workout, participants rested for 5 mins. to begin the heart rate variability assessment. Afterwards, we collected data for 1 min (Nakamura et al., 2015) using their chest band with a portable device (Polar H10, Kempele, Finland) connected to a smartphone with a mobile app software (Elite HRV, Asheville, North Carolina, USA), meanwhile participants were laid down on the stretcher and kept a spontaneous breath (Saboul et al., 2013). We converted the indices obtained into a natural logarithm of the root mean square differences between adjacent R-R intervals (LnRMSSD) which is considered the most sensitive measure of fatigue level in a short time (Esco et al., 2017). We present data as percentage of changes between pre-warm-up and post workout measurement.

Statistical analysis

We compared performance in workouts throughout the unpaired t-test between two groups: Inexperienced Group (IG) and Experienced Group (EG) in variables of “repetitions” in AMRAP and “total time” in FT. However, we used a two-way mixed analysis of variance (ANOVA with two factors: workout and expertise level, and three and two levels, respectively) to compare the data reflecting exercise (RPE, jumping, blood lactate, heart rate and variability). We performed pairwise comparisons based on Bonferroni criterion when any main effect was observed. Besides, we checked ANOVA assumptions by normality, homoscedasticity, and independence tests (Shapiro-Wilk, Levene, and Durbin-Watson tests, respectively). We present all data as their means (M) and standard deviations (SD). In the general linear model, we calculated effect size (ES) based on Hedges’ g (Hedges, 1981) and interpreted according to

Hopkins (2002). Previously to analysis, we calculated the ideal sample size to ensure enough statistical power (Whitley & Ball, 2002). A priori sample size analysis was based on Cohen's f large effect size (Cohen, 1988), setting statistical power at .8, and alpha at .05. We set statistical significance at $p < .05$. All statistical tests and plots were performed with RStudio (v4.0.2).

RESULTS

The preliminary examination of sample size revealed that a minimum of 20 participants was attained, satisfying the criterion for statistical power. Furthermore, all assumptions necessary for conducting ANOVA, including independence of observations, normality of residuals, and homogeneity of variances, were diligently verified across all variables. With these foundational prerequisites met, the subsequent analytical work aimed to delve deeper into the relationship between the kind of workout and participants' varying levels of expertise in performance, RPE, Lac, CMJ, heart rate and HRV. Firstly, we analysed the sex as a factor but no influences were found, therefore, the following analyses were performed as a single group. We report descriptive data in Table 3, sorted by kind of workout and expertise level. This description results from the idea that the kind of workout has an influence on performance depending on the participant's expertise. In this sense, the performance, considered as repetitions, in AMRAP showed differences between level groups (ES = 0.81, $p = .044$). However, when participants performed FT based on AMRAP achievement, differences dimmed (Figure 3).

We found no differences in RPE between experienced and beginning athletes. However, main effect in the kind of workout was showed ($F(2,46) = 11.003$; $p < .001$). Specifically, the expert group reported differences between workouts, pointing at FT and EMOM as the ones that required the most and the least effort (Figure 4A), respectively. Whilst the IG only reported differences between FT and EMOM (ES = 0.97, $p = .02$).

With respect to changes in Lac, participants showed an increment in all types of workouts (Table 3). FT registered the highest Lac, and EMOM the lowest (ES = 1.05, $p < .001$) in both expertise groups (Figure 4B). Additionally, these differences between workouts ($F(2,46) = 7.669$; $p < .001$) were more pronounced between FT and EMOM distributions in both expertise groups (IG: ES = 1.1, $p = .01$; EG: ES = 1.0, $p = .01$, respectively). However, we found no significant differences between groups when participants performed the same workout.

Participants showed worse performances in CMJ after AMRAP in both groups (IG: ES = 1.19, $p < .001$; EG: ES = 0.81, $p = .013$) and in IG immediately after FT workout (ES = 1.19, $p = .006$), but this fact did not happen after EMOM. Despite the decrease, we found no differences as percentage of change between expertise groups and workout (Figure 4C).

Regarding HR, we found no difference between expertise levels in HRmean and HRmax records through each session (Figures 4D & 4E). However, we did not obtained differences between workout or subject's experience. Nevertheless, acute change in HRV (Figure 4F) showed main effects in workout ($F(2,46) = 7.381$; $p < .01$) and expertise ($F(1,23) = 4.657$; $p = .034$) although post-hoc based on Bonferroni showed a decrease only stood out in AMRAP and FT comparison for IG (ES = 1.08, $p = .001$).

Table 3. Athletes' descriptive statistics for RPE (0-10), HRmean/HRMax (bpm) and pre-post difference in CMJ (cm), HRV (RMSSD) and La+ increased (mmol/l). All variables with mean ± SD attend to experience level. Comparisons between AMRAP vs FOR TIME vs EMOM and effect size (ES) between pre-post measures.

		Inexperienced			***Experienced***		
Variable /WOD		AMRAP	FT	EMOM	AMRAP	FT	EMOM
RPE		7.5 ± 0.9	8.0 ± 0.8*	7.0 ± 6.3*	7.1 ± 1.1*	7.9 ± 1.1*	6.3 ± 0.9*
HRmean (bpm)		165.6 ± 8.2	164.3 ± 9.3	164.2 ± 6.4	166.1 ± 9.5	166.5 ± 12.7	162.4 ± 10.7
HRMax (bpm)		179.2 ± 7.6	180.9 ± 8.5*	178.6 ± 7.2*	181.6 ± 12.1	182.7 ± 12.5	181.5 ± 11.9
CMJ (cm)	***Pre***	32.7 ± 7.7	33.2 ± 8.5	31.7 ± 8.3	37.6 ± 4.2	38.1 ± 4.7	38.6 ± 3.5
	Post	31.3 ± 7.6*	31.4 ± 7.9*	30.8 ± 7.8	36.1 ± 3.9 *	37.2 ± 4.5	37.8 ± 3.6
	ES	(1.2)	(1.2)	(0.3)	(0.8)	(0.5)	(0.2)
LA (mmol/L)	***Pre***	2.3 ± 0.6	1.8 ± 0.6	1.9 ± 0.9	2.4 ± 0.7	2.4 ± 0.8	2.3 ± 0.8
	Post	10.8 ± 2.9*	11.9 ± 3.0*	9.2 ± 2.8*	10.2 ± 2.9*	11.4 ± 4.1*	8.1 ± 2.8*
	ES	(3.9)	(4.5)	(3.3)	(3.4)	(2.9)	(2.8)
HRV (RMSSD)	***Pre***	61.8 ± 9.6	60.2 ± 7.6	63.5 ± 2.4	62.3 ± 10.7	57.9 ± 7.8	63.3 ± 9.3
	Post	48.9 ± 12*	36.4 ± 12.1*	36.2 ± 12.2*	39.4 ± 16.5*	30.7 ± 11.9*	28.9 ± 9.6*
	ES	(1.2)	(2.3)	(2.5)	(1.6)	(2.6)	(3.5)

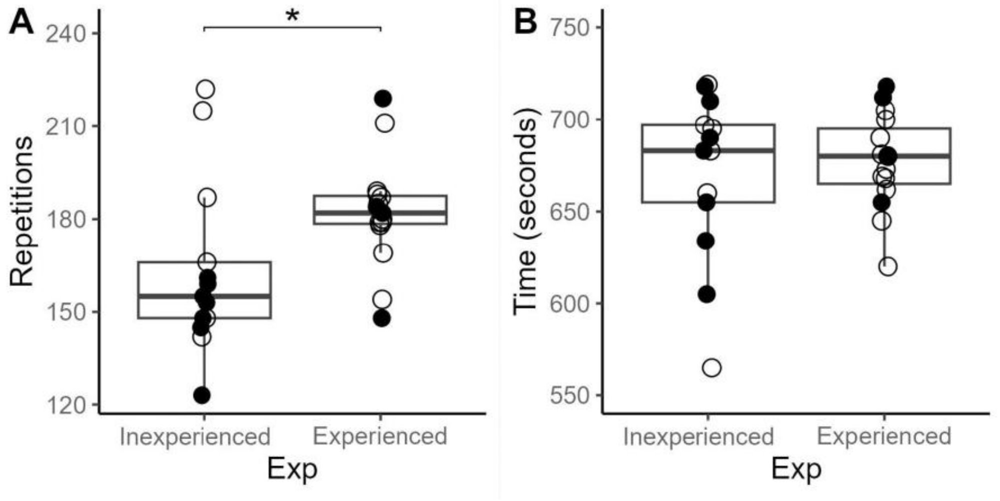


Figure 3. Performance in repetitions in AMRAP and finish time in FOR TIME, attending to the experience level of participnats. Empty dosts mean women and fill dots men. (A) AMRAP; (B) For time

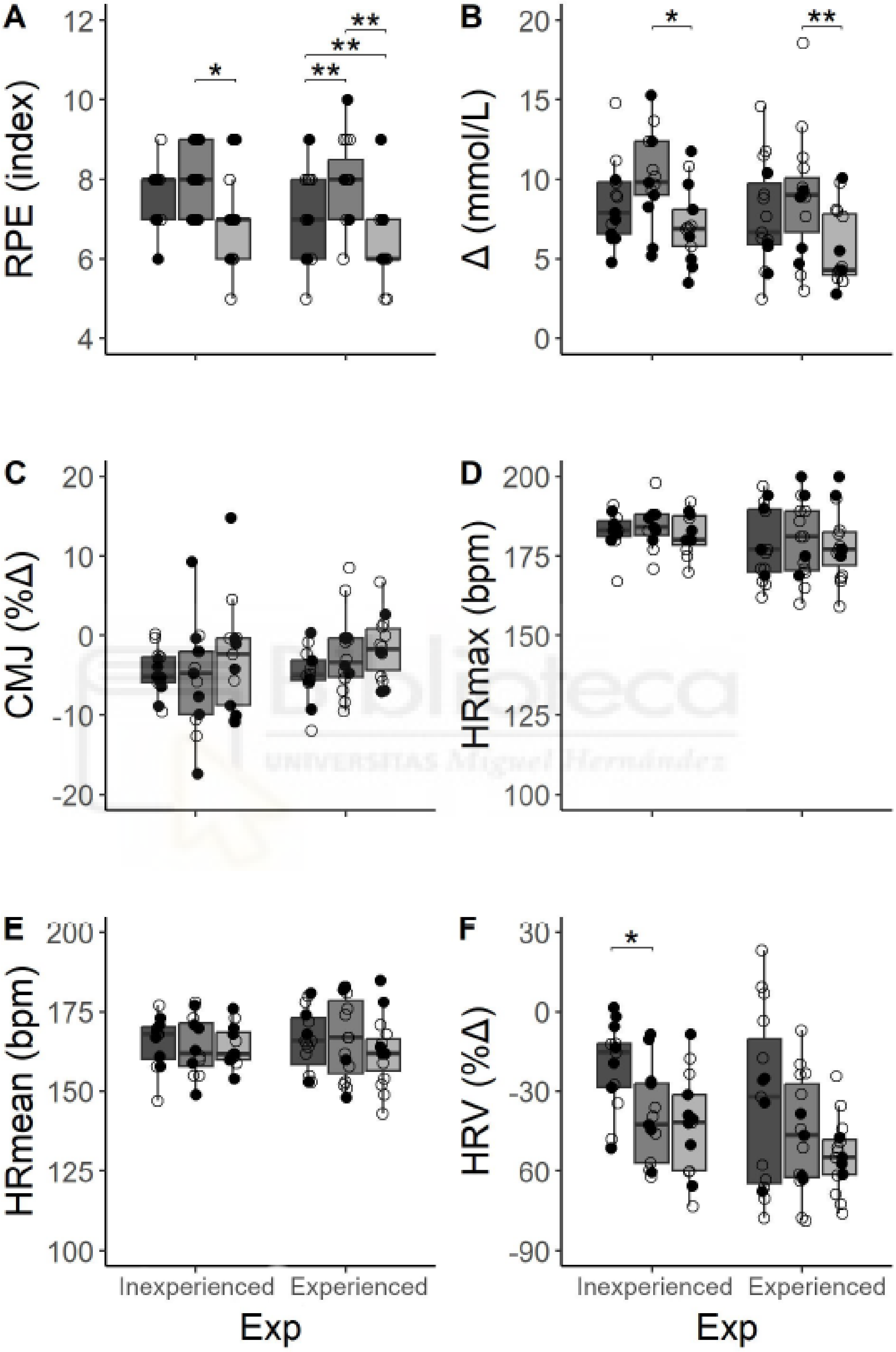


Figure 4. Comparisons of acute measurements between three WODs distributions depending on level of experience (Exp) in CF training (Beginner < 2 years; Experienced >2 years) and WOD type (blue=AMRAP; yellow=FOR TIME; red=EMOM). Empty dots mean women and fill dots men.

DISCUSSION

FFT has three typical distributions for the main high-intensity part focusing on the total of repetitions, the limit time, or the effort/rest ratio that coaches use to schedule their athletes' training (Maté-Muñoz et al., 2018). Currently, there are no scientific reports comparing AMRAP, EMOM and FT distributions, matching training intensity and training volume for each participant and measuring acute effects. Therefore, to our knowledge, this is the first study aimed at describing the acute responses after performing three types of training with a similar volume and relative intensity which were organized in different workout distributions. Moreover, our hypothesis was confirmed as the results reflected how the FT format increased the acute responses than structures such as AMRAP or EMOM. Specifically, FT elicits higher responses in lactate and RPE compared to AMRAP, while EMOM results in lower neuromuscular fatigue and lactate due to scheduled rest, especially in athletes with more than 24 months of experience in FFT. Concerning performance, the measurements in repetitions for AMRAP showed that the EG have a better performance in spite of both groups lifting an individualised load, which means that the relative load is equal for all participants. This study's results are in line with Butcher et al. (2015) showing that the EG performed a slightly higher number of repetitions in AMRAP, even though in this study we classified the EG as those who had only been practising for more than eight months.

What is more, participants reported different perceived effort depending on the type of workout although the training load was equal among them. The values manifested by the athletes are in line with the study of Timón et al. (2019), in which the participants showed a perceived effort of "vigorous activity" in AMRAP, yet higher for FT training where they described its intensity as a "very hard activity". In this sense, providing a "Time Cap" to complete a standardised number of repetitions and the feedback of a coach to achieve the best time may suggest that athletes worked harder in an FT. On the contrary, athletes in the advanced group declared a perceived effort after EMOM with a mean of 6.3 over 10, which may be translated as "moderate to vigorous activity". This difference in EMOM between groups results from the EG completing the repetitions of every EMOM round in less time than the IG; they also had more time to rest until the next minute, therefore this type of work meant less effort for them (De-Oliveira et al., 2021).

Regarding the physiological response, all participants showed a significant difference in Lac between FT and EMOM training. Regardless of the athlete's expertise level, these results might show a scalable relationship among workouts since a similar trend could be seen in the IG and EG, with the lowest lactate levels after EMOM, followed by AMRAP and the highest lactate levels after FT. A similar study (Timón et al., 2019) compared AMRAP with FOR TIME and reported that experienced FFT athletes show significant differences in high lactate levels in FT with respect to AMRAP. Moreover, the fact that lactate values are in line with those in previous research, where they were reported to be around 10 mmol/L in similar workouts (Maté-Muñoz et al., 2018; Tibana et al., 2016), might support the idea that the type of workout could trigger a different physiological response. Despite this, lactate levels can be much higher depending on the muscle mass recruited by the exercises in the workout, the intensity of the participants for a training or a competition workout, or as can be seen in this work, the distribution of the training. For example, Fernández-Fernández (2015) found up to 14 mmol/L in "Fran" and "Cindy" workouts (despite their different durations) when experienced athletes performed max effort for a personal record in a familiar workout.

Regarding neuromuscular fatigue after the three workouts, athletes reached lower height in CMJ in comparison with pre-test in AMRAP, and FT in IG, but this difference was not found in EMOM for any group. Moreover, no significant differences were identified in CMJ height loss between FFT modalities or between the experience level of the participants. The present results contrast with Banja et al. (2023) , who showed a significant decrease in CMJ height after a workout, "Fran" (FT), for experienced participants. Maté-Muñoz et al. (2018) found the same results in this workout although this study was performed with Inexperienced participants and, in this case, the present results are in line. Moreover, these same authors saw a significant difference in the jump's height after a gymnastic workout called "Cindy" (AMRAP), but they did not report differences after an endurance workout with low-intensity cyclic movements. Eventually, in some scientific works providing evidence of responses on jump performance after a workout with weightlifting exercises, participants reduced their jump ability between an average of 3% and 5% (Oliver-Lopez et al., 2022). Thus, this paper shows the same results in lower CMJ height with the exception of EMOM training, where a decrease between 1% and 3% in CMJ height would indicate that this distribution produces less mechanical fatigue due to rest intervals.

In addition, HRmax in FT reached the highest values of the three workouts in the IG with respect to EMOM although we found no statistically significant among workouts, in bpm values of HRmean and HRmax. These results agree with the scientific reports in which the load is matched for AMRAP and FOR TIME trainings (Toledo et al., 2021). Furthermore, the impact of these workouts on the athletes' parasympathetic nervous system resulted in a large drop in RMSSD values; the comparison among FFT modalities only showed a large difference between AMRAP and FT in IG, where the second workout modality had a greater effect on the decrease in HRV. The results in the literature are quite conclusive in terms of the acute impact on HRV of participants after workouts, but it should be noted that new research is emerging using the measurement of HRV on a day-to-day basis and how it evolves at rest (on waking up in the morning) when FFT is implemented in order to monitor an additional variable in the athletes' training load (Castanheira et al., 2023; Williams et al., 2017).

Despite the fact that there is little evidence in the literature in which several schemes of workouts are compared, we consider that the current study might raise some concerns. Firstly, we made the homogenization of workouts based on performance in AMRAP. Thus, we found an apparently light imbalance between the time of performance in AMRAP and FT (the second workout was performed faster than the first). Therefore, future studies need to compare the effect on workouts when they are homogenised based on FT or another workout and vice versa. Secondly, the EMOM structure might have had an influence on the athlete's performance since an experienced athlete's capacity allows for a higher number of repetitions. In this sense, some athletes needed to carry out additional rounds and therefore the load in each minute could have been unequal among athletes. Thirdly, we performed this research in an ecological environment, thus the study design needed adjustment to the competition calendar. This fact did not allow a more extended study, which enabled an inversion of the protocol so as to delve into the effect of creating workouts based on FT or EMOM instead of AMRAP alone. Fourth, and finally, participants have a significant age difference, but the characteristics and backgrounds of both groups naturally result in EG being older than IG. Additionally, a larger sample size would have been ideal to enhance the robustness of the comparisons between groups.

Practical applications

This study provides sufficient data to identify specific cardiovascular, metabolic and perceived exertion responses to three different ways of performing a workout. Therefore, coaches should be aware that training distribution is a determinant of success in the desired training stimulus for each session. The structure and feedback of the workout elicit different responses in participants and different modalities must be used depending on their experience and FFT level. In addition, coaches should adapt training based on training weeks, e.g. FT may be appropriate for athletes following a rest weekend, whereas AMRAP or EMOM with extended rest may be preferable for those who have accumulated fatigue during the week to avoid overtraining.

CONCLUSIONS

The type of workout in the three known modalities (“AMRAP”, “FOR TIME” and “EMOM”) can change the training stimulus. Acute responses will be different depending on the type of workout for a similar load. Additionally, FT produces a higher acute response in markers such as lactate and RPE, compared to an AMRAP. An EMOM structure will have less neuromuscular fatigue or blood lactate due to rest time intervals, especially for experienced athletes. Future research could investigate the chronic adaptations of athletes following FFT programs considering the workout distribution depending on the experience or recovery level or following a random design of modalities distribution independently of their responses.

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APPENDIX 2.

Note: This study was published.

8.2 STUDY 2: Oliver-López, A., García-Valverde, A., & Sabido, R. (2024). Standardized vs. Relative Intensity in CrossFit. *International Journal of Sports Medicine, 45*(04), 301-308. http://doi.org/10.1055/a-2204-2953

8. Chapter 8: Appendices. Appendix 2

Study 2: Standardized vs. Relative Intensity in CrossFit

ABSTRACT

CrossFit is characterized by being a standardized training program that improves physical performance through the provision of several stimuli regardless of the participant's strength level. This study aimed to compare the acute response in total repetitions as a measurement of performance, jump ability, physiological demand (heart rate and blood lactate), and perceived effort considering the participants' strength level with individualized intensity in CrossFit.

Thirty-five participants were assessed and asked to participate on two separate days in a standardized and relative 'As Many Repetitions As Possible' (AMRAP) CrossFit circuit. Both AMRAPs comprised strength, gymnastic and aerobic exercises, although only strength was individualized according to the participant's level. Before the statistical analysis, participants were allocated to higher- or lower-strength groups following the one-repetition maximum-bodyweight ratio in the push press exercise.

Results support the existence of a strong relationship between strength level and total repetitions in both AMRAPs. In addition, differences in total repetitions and rate of perceived exertion between strength groups are discarded when AMRAP intensity is individualized while physiological demand and jump ability are maintained. Thus, the higher-strength participants may benefit from similar responses with a lower number of repetitions.

Therefore, CrossFit trainers should be encouraged to prescribe strength tasks based on the percentage of 1RM for every training.

Key words: High-intensity resistance training, acute response, resistance.

INTRODUCTION

CrossFit (CF) is a popular sport regimen characterized by high-intensity interval training [1], high demands of muscular strength [2], and functional exercises. CF is often a mix of weightlifting (e.g. power clean), powerlifting (e.g. deadlift), gymnastics (e.g. muscle-up), and endurance (e.g. running) exercises [3]. One example of a typical CF circuit is known as AMRAP, in which athletes should perform *As Many Repetitions/Rounds as Possible* over a set amount of time. In this case, each participant adopts a particular approach to their pace [4] because they do not have the option to take breaks during the task, and the weight that needs to be lifted is usually the same for all participants [5], regardless of individual performance differences.

According to sports science literature, exercises should be individualized so as to maximize the effectiveness of training [6,7]. In order to prescribe a specific effort during training, standardized intensity could be an incorrect strategy to maximize training effects in a group of participants with heterogeneous performances, due to their experience in the discipline [8], strength or body composition [9]. In this sense, relative intensity such as the percentage of the participant's maximum capacity has been proposed as a criterion since it has shown relevance and importance for the training effect on performance [4]. For example, previous research has shown that resistance training at 30% for 1 RM has a minimal effect on hypertrophy processes compared to higher intensities [10].

Moreover, results from weightlifters and American Football players confirm the necessity of relativized loads (>80 % 1RM) to improve maximal strength, reach peak performance in vertical jump power, and produce hypertrophy and strength improvements in advanced participants. In addition, untrained subjects also improved with relativized load, although through a different "mechanism": the neural adaptations and neuromuscular response to strength training appear as early adaptations in beginner participants [11–13]. On the contrary, a recent study by Prieske et al. [14] demonstrates that short-term individualized and standardized light to moderate loads (50-80% 1RM) with regular training were equally effective in improving measures of muscle strength and vertical jump performance in young participants (men under 18 year of age).

Therefore, the participants' effort during equal absolute intensity, as happens in CF "Workout of the Day" (WOD), could be unequal depending on their own performance level. This may reflect inadequate management of the training load and different perceptions of intensity for participants [15]. Consequently, said management could result in different fatigue levels as well as changes in acute performance [5,16] and undesired adaptations or injuries due to overload [17–19].

Thus, the objective of the study was to evaluate the acute effects on participants' performance when the same WOD is performed with different intensity prescriptions (standardized vs. relative load).

HYPOTHESIS: Strong and weak participants would face similar performance and physical demands when the WOD is executed with a relative load in comparison to standardized WODs.

MATERIALS AND METHODS

Participants

Thirty-five participants were enrolled in this study, including 17 males and 18 females (Table 1) from several CF training centers. All of them met the following inclusion criteria to take part in the study: (i) having at least three months of experience in CF; (ii) achieving 1RM on the push press higher than 50 kg for males and 35 kg for females; (iii) and being free of pathologies or injuries that could affect their health or the study. In addition, those with maximal lift push-press to body weight ratios (PP/BW) below 0.8 (women) and 1.1 (men) were assigned to the Lower Strength (LS) group. Otherwise, those with PP/BW values at or above the cut-off points were assigned to the Higher Strength (HS) group [20].

Table 1. Athletes' descriptive characteristics (mean ± standard deviation) according to strength level.

	Lower Strength group (women = 7, men = 11)	**Higher Strength group (women = 11, men = 6)**
Age (years)	33 ± 7	34 ± 7
Height (cm)	171 ± 10	166 ± 7
Body Weight (kg)	75.7 ± 13.8	64.1 ± 10.3
CF experience (months)	33.2 ± 30.4	56.7 ± 35.0*
Ratio[1]	0.85 ± 0.17	1.03 ± 0.13*
[1]maximal weight lifted in push press divided by bodyweight; *$p < 0.05$.		

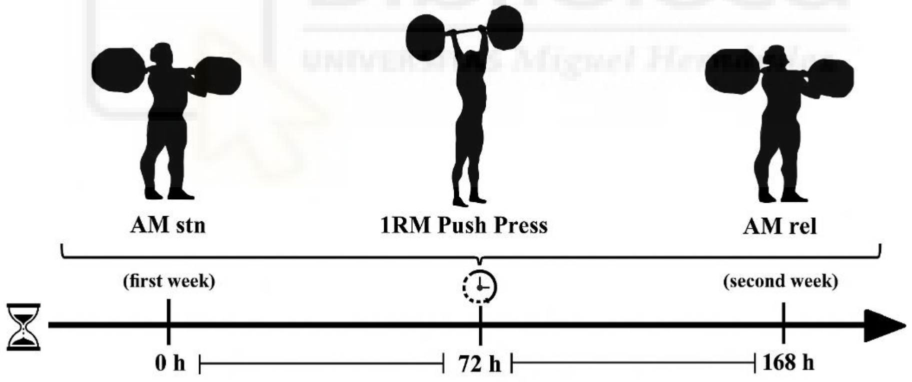

Fig. 1. Study design and timeline used to evaluate the acute effects on athletes' performance. AMstn = Standarized AMRAP; AMrel = Relativized AMRAP.

Prior to the WOD, participants were instructed to abstain from engaging in any physical activity for 48 hours, and to avoid consuming any food or stimulant drinks within a three-hour window. Before enrolling in the study, all participants were informed about the protocol, potential risks and signed informed written consent. This study was developed following the guidelines in the Declaration of Helsinki and the regulations issued by the research committee of the Miguel Hernández University (Ethics Committee ID: 230210121042).

Study design

The participants visited the laboratory three times, with each session separated by a 72-hour interval. All sessions were performed at the same time of the day for each participant. They performed a daily warm-up routine consisting of a five-minute jog, three sets of 10 repetitions of joint mobility exercises (including push-up to bear, lunge with thoracic rotation, and pull-down movements using a resistance band), and two sets of progressively intense movements from the WOD. The first and third sessions were training days in which WODs were performed, and on the second day, participants were assessed with a one-rep max on push press which was performed according to NSCA guidelines [21] ´ (Figure 1). The push press was chosen as the reference exercise because it is a limiting exercise in the WOD, so it may be relativized accordingly with the exercise with the lowest weight lifted.

Every training day was related to a WOD-type AMRAP (Smith et al.,2013). The first of them was performed with standardized intensity, whereas the other was carried out with relative intensity (75%) 1RM Push Press for weightlifting exercises. Both WODs had a length of 12 minutes (Table 2). Performance (number of repetitions in WOD), rate of perceived effort, change in jump ability, blood lactate and heart rate were recorded in every WOD (Figure 2).

Procedures

Repetitions.

Each WOD was performed under the supervision of two qualified coaches with a "CrossFit® Judges Course" certification to ensure that movement and workout standards were met. Coaches had an overview of the knowledge and skills necessary as if it were a competition, including movement requirements and common mistakes, to count the good repetitions of each participant during both WODs. To merge aerobic and strength training in the same measurement, judges were asked to count one repetition for every 25 m of running.

Perceived effort.

The rating of perceived exertion values was obtained using the Borg category scale (CR-10) [22]. The CR-10 scale consists of an exercise intensity scale defined by rest shown as '0' minimum, and maximal as '10'. Participants were asked, 'How hard do you feel the WOD was?', 30 minutes following the conclusion of the WODs.

Jump ability.

Jump height was assessed by Globus mat (Ergo Tester, Codognè, Italy) at the end of the warm-up and immediately after completing the WOD. All participants performed six progressive CMJs after warm-up and then were asked to do three as-high-as-possible CMJs with one minute of rest. The criteria for a valid CMJ included keeping the hands on the waist throughout the entire test and landing with extended knees. Rebound-on landing was allowed through flexo-extension of ankles; the first contact with the mat stopped the stopwatch. The best height in the last three CMJs was noted as the jump height in centimeters.

Peripheral blood lactate concentration.

Blood lactate concentration was determined by an average of test strips and a portable analyzer (Lactate Scout Plus, Biolaster, Gipuzkoa, Spain) in peripheral blood samples taken from the left earlobe one minute after warm-up (basal) and upon completion of the WOD following the CMJs [23]. Prior to extracting the sample, the skin was cleaned with chlorhexidine. For analysis, the first two blood drops were discarded, and the third was used.

Table 2. Descriptive volume and intensity for each exercise.

Exercise	WOD 1		WOD 2	
	Volume	Intensity	Volume	Intensity
Power clean	5 rep	50 kg (men); 35 kg (Women)	5 rep	75% 1RM
Push press	3 rep	50 kg (men); 35 kg (Women)	3 rep	75% 1RM
Pull up	5 rep	Body weight	5 rep	Body weight
Push up	8 rep	Body weight	8 rep	Body weight
Air Squat	10 rep	Body weight	10 rep	Body weight
Run	150 m	Free	150 m	Free

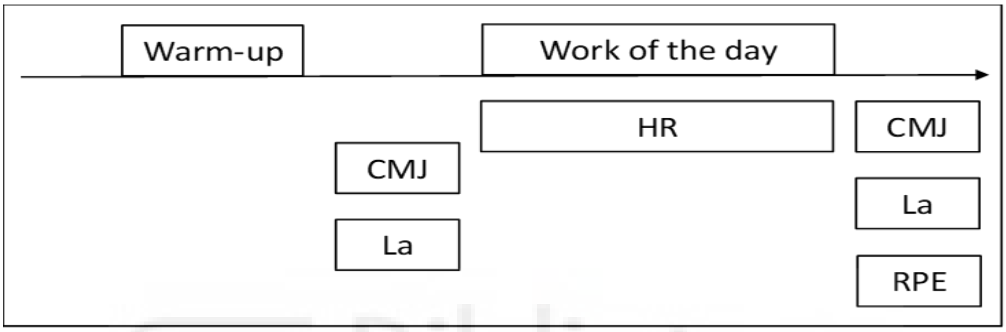

Fig. 2 Session design. WOD = 'Work of the Day' means the training in CrossFit slang. CMJ = countermovement jump, La + = blood lactate, HR = heart rate, RPE = rating of perceived effort.

Heart Rate.

During both WODs, participants wore a chest band placed on the Xiphoid area of the sternum with a portable device (Polar H10, Kempele, Finland) to record the heart rate (HR). A smartphone app (Polar Team, Kempele, Finland) was used to record the performance of several participants simultaneously. At the end of every 12-minute AMRAP, HR average (HRmean) and HR peak (HRpeak) were collected. In addition, the heart rate was compared with the theoretical maximum, which was calculated by Tanaka's equation [24]: 208-0.7*age.

Statistical analysis

Relationships between categorized variables (1RM/B.W. ratio and performance in both WODs) were quantified by calculating Pearson´s correlation. Correlations were interpreted using modified Cohen's criteria: very small (<.10), small (.10-.29), moderate (.30-.49), large (.50-.69), very large (.70-.89), or extremely large (>.90) relationship [25][19]. An analysis of variance was conducted with two factors (two-way ANOVA with two levels: type of WOD and strength level). Pairwise comparisons were performed following the Bonferroni criterion. ANOVA assumptions were checked by normality, homoscedasticity, and independence tests (Shapiro-Wilk, Levene, and Durbin-Watson tests, respectively), which were met in all analyses. Moreover, the effect size based on Hedges' g [26] was calculated using a spreadsheet and interpreted according to Hopkins [25][19]. Statistical significance was defined as $p < .05$. Analysis and figures were designed using RStudio (v4.0.2).

RESULTS

The results (Figure 3) showed that strength level had a very large correlation with the number of repetitions in the standardized AMRAP (r = .72, p < .05). Similarly, the results indicated a significant positive correlation between strength level and performance in the relativized WOD (r = .58, p < .05). The comparison between WOD repetitions showed differences in the stronger group, with a lower number of repetitions during the standardized WOD (ES = 1.2, p = .033). Notwithstanding, these results were not found for weaker participants who hardly changed the number of repetitions in a relativized WOD (Figure 4A).

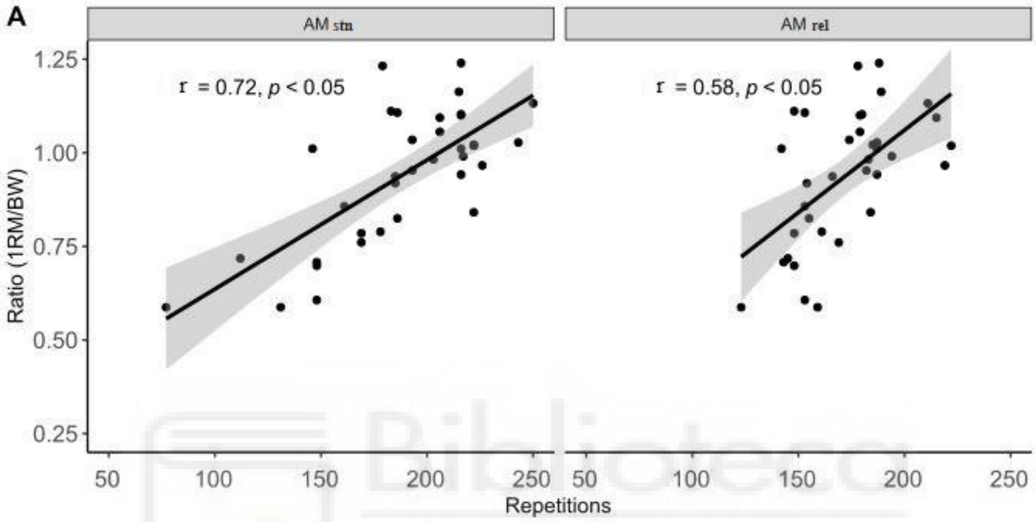

Fig. 3. Association between WODs performance in repetitions (AM stn = standardized, AM rel = relative load) with 1RM Push Press/BW ratio of the participants. The solid triangle refers to men and the solid circle refers to women.

Furthermore, differences were identified between strength levels in the ratio of perceived exertion in standardized WODs (ES = 0.75, p = .032). What is more, the stronger group reported higher perceived effort after performing the standardized WOD compared with the relativized one (ES = 0.7, p = .006) (Figure 4B). Additionally, a significant difference in RPE between groups in the standardized AMRAP was found, where the LS group showed a higher level in the ratio of perceived exertion with respect to the HS group. This difference is not observed in the relativized WOD.

Table 4 shows that HS group demonstrated a significant decrease in CMJ results between the pre- and post-tests for both WODs (AMRAP stn: ES = 0.3, p<.05; AMRAP rel: ES = 0.3, p<.05) whereas LS ones did so only in the relativized AMRAP (ES = 0.2, p<.05). However, no significant differences in jump loss were found between the standardized and the relative load WOD or strength level group (Figure 4A).

Lactate concentration increased in all participants in both WODs, which showed differences between pre- and post-training measurements in every AMRAP (Table 3). After completing both WODs, participants reached a blood lactate concentration of approximately 10 mmol/L (Table 4). However, there were no differences in lactate increments between WODs or strength groups (Figure 4D).

Lastly, HR_{peak} showed high values (> 90% of theoretical HR_{peak}) regardless of the participant's strength level although no differences were found between WODs. Likewise, HR_{mean} had no differences between groups but the relativized WOD was found to be more demanding than the standardized WOD for the LS group (*ES* = 0.4, *p* = .024) (Figure 4E and 4F).

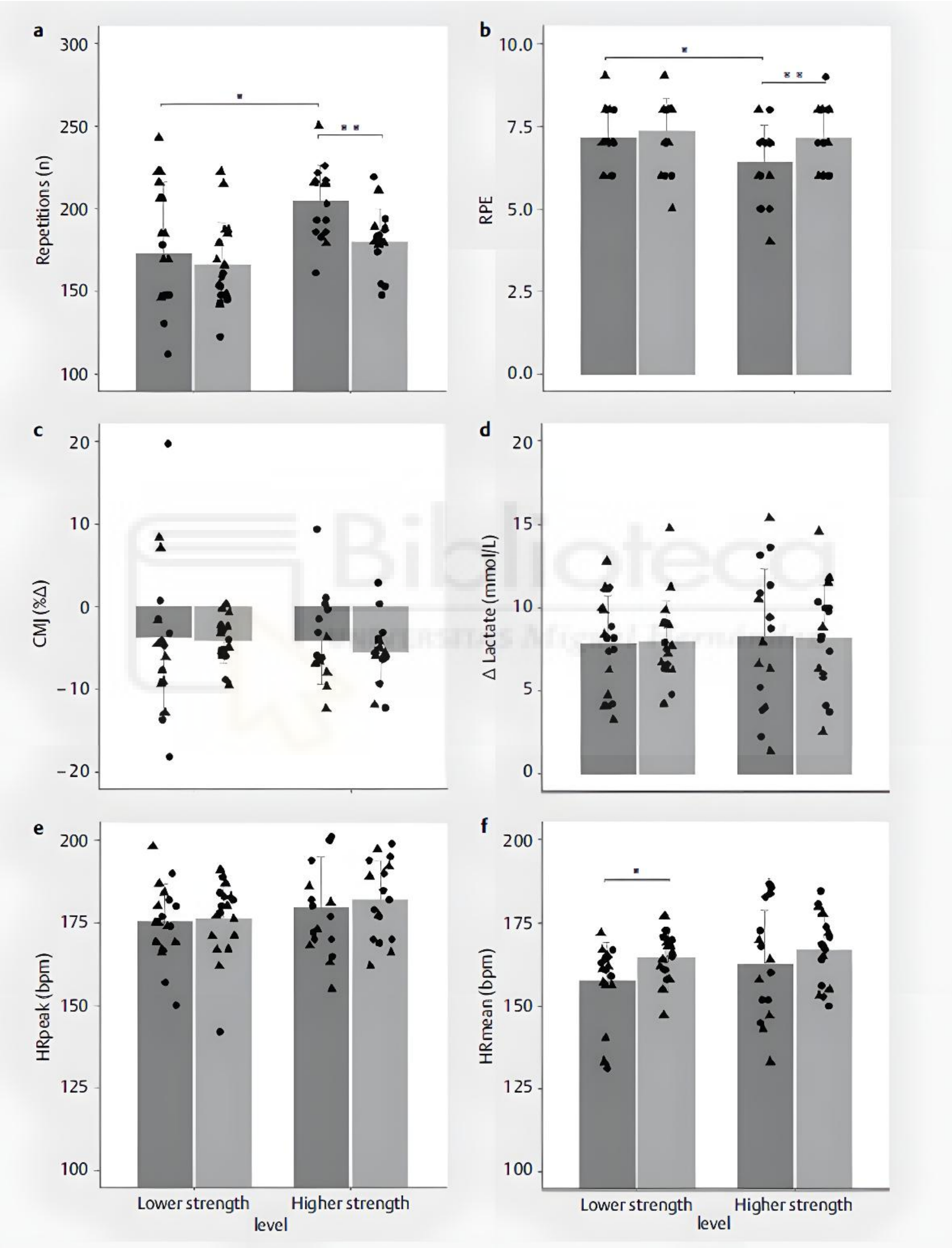

Fig. 4. Comparisons between pre-post depending on 1RM PP/BW ratio (stronger men < 1.1 kg/BW; stronger women > 0.8 kg/BW) and AMRAP type (black = standardized; grey = relative). a) Comparison in repetition; b) Comparison in RPE reported; c) Comparison in the percentage of change in countermovement jump; d) Comparison in increment of blood lactate; e) Comparison in heart rate peak; f) Comparison in heart rate mean. The solid triangle refers to men and the solid circle refers to women. *= p < 0.05; **= p < 0.01.

Table 3. Athletes' descriptive statistics as mean ± SD. Comparisons between AMRAP standardized vs relativized and effect size (ES).

	LS group (women = 7, men = 11)			HS group (women = 11, men = 6)		
Variable	AMRAP stn	AMRAP rel	ES	AMRAP stn	AMRAP rel	ES
CMJ (cm)	-1.31 ± 2.83	-1.09 ± 1.54	0.1	-1.52 ± 1.90	-1.85 ± 1.65	0.2
ΔLa (mmol/L)	7.03 ± 2.92	8.24 ± 4.1	0.3	7.96 ± 2.45	7.75 ± 3.75	0.1
HRmean (bpm)	156 ± 13.0	162 ± 13.7 *	0.4	163 ± 16.4	167 ± 10.8	0.3
HRmax (bpm)	175 ± 11.5	176 ± 11.7	0.1	179 ± 15.5	182 ± 11.8	0.2
RPE	7.17 ± 0.86	7.33 ± 1.03	0.2	6.41 ± 1.12	7.12 ± 0.99 *	0.7
Reps (n)	173 ± 43.0	166 ± 25.9	0.2	205 ± 21.8	180 ± 19.4 *	1.2

* $p < .05$; ES = Effect size; LS = Lower Strength; HS = Higher Strength; CMJ = height countermovement jump loss; ΔLa = Lactate increment; HRmean = mean of heart rate over WOD; HRmax = peak of heart rate over WOD; RPE = ratio of perceived exertion index; Reps = repetition performed.

Table 4. Athletes' descriptive statistics for La+ and CMJ pre and post WOD (mean ± standard deviation) attend to strength level. Comparisons pre-post and effect size (ES).

		AMRAP stn			**AMRAP rel**		
Variable	Participants	Pre	Post	ES	Pre	Post	ES
CMJ (cm)	LS	33.2± 7.33	31.9± 6.72	0.04	34.2± 6.92	33.1± 7.01*	0.2
	HS	35.3± 5.01	33.7± 4.47*	0.3	34.6± 5.47	32.8± 5.38*	0.3
La (mmol/L)	LS	2.34± 0.9	10.2± 2.51*	4.1	2.33± 0.66	10.3± 2.53*	4.2
	HS	1.99± 0.95	10.2 ± 4.2*	2.6	2.14± 0.78	9.89± 3.68*	2.1

* $p < .05$; ES = Effect size; LS = Lower Strength; HS = Higher Strength; CMJ = height countermovement jump; La = Blood lactate increment.

DISCUSSION

Many CrossFit coaches use a scaled training regimen, which is performed by participants according to their fitness level. Yet, sports scientists recommend individualizing training parameters such as intensity since these could provide an optimized effect [27–29]. However, there is currently no evidence to support the use of individualized loads during WODs in CrossFit training. Therefore, this study aimed to compare the performance and acute effects between the same WODs carried out with standardized and relativized intensity prescriptions, paying attention to the participants' strength levels. In this sense, our results showed that repetitions and ratings of perceived effort were homogenized when participants performed a relativized WOD. Besides, only the higher-strength group showed differences between standardized and relativized WOD. All other variables did not show a change between groups and WOD.

Regarding repetitions in WODs, Bellar et al. [8], reported experienced participants performed significantly more repetitions on the standardized AMRAP compared to the inexperienced group, showing that the participants' experience is a key component of performance in CF workouts. It should be noted that experience seems to lead to an optimization of technique that allows for improved performance [30]. In contrast, Butcher et al [31] showed in a relativized WOD that the experienced group tended to obtain slightly higher scores in AMRAP performance. In the present study, there was no attempt to stratify or measure the level of fitness of the participants in either the experienced or amateur group.

The rate of effort in CF is often identified as "very hard" or "very, very hard" in several research papers [32–35] regardless of the kind of WOD. In fact, RPE values reported in this study agree with the latest literature. However, our results disagree with Butcher et al [31] as regards RPE because they used relativized WODs for strength and gymnastic movements. In this sense, standardized WODs showed differences in fatigue perception between LS and HS participants which did not happen in relativized WODs. Additionally, due to the relativization of the WOD, RPE in the HS group increased, which supports the idea of a homogenization effect regardless of strength or expertise level. Thus, RPE could be a good marker for monitoring fatigue no matter what the participant's performance level is [36].

Neuromuscular responses measured through jump ability were expected to decrease after both WODs in every group. Maia et al. [37] and Prado-Dantas [38] provided evidence of acute effects on jump performance after a WOD with weightlifting exercises. Similar results have been observed in our study where both groups reduced their jump ability between 3% and 5% in the different WODs. The LS group showed a significant decrease during the relativized WOD, but not during the standard one. These results are in line with Maté-Muñoz et al [32] who found that inexperienced participants decreased their performance immediately after finishing a similar WOD schedule to that in our study. Our results on standardized WODs cannot be compared with those in previous studies because in order to complete standardized workouts they deem that a minimal participant fitness level is necessary. For instance, studies like Serafini et al. [39] or Sousa-Neto et al. [40] do not consider including inexperienced participants in their research. However, both WODs seem to have had a similar effect in the HS group with a significant decrease. Therefore, the participants' fatigue level could be monitored through CMJ testing after strength micro-cycles or intra-sessions [41,42], and it may be a tool to discriminate between workouts for LS participants.

Additionally, blood lactate concentration did not show any differences between groups and WODs, but participants achieved values close to those of other studies in which the WOD was designed with similar exercises and load. In this sense, several authors [1,32,43] also reported [La] around 10 mmol/L after WODs. Therefore, moderate lacticaemia could be assumed as specific to high-intensity WODs regardless of the participant's strength level although several lactate concentrations have been reported in the literature depending on the type of WOD. Nevertheless, higher [La] could be achieved depending on effort demand. Fernández-Fernández [44] found up to 14 mmol/L regardless of the length of the WOD (e.g. "Fran" or "Cindy" WODs) when they are performed in order to break a personal record, and similar results were highlighted by Perciavalle [45] when participants performed qualifying WODs for a competition, which can be explained due to the maximum intensity at which the participants performed the WODs.

On the other hand, heart rate has been related to cardiovascular and physiological demands in CF, which was studied by several researchers. Butcher et al [31], who performed a high-intensity continuous WOD similar to ours, reported values of HR_{mean} and HR_{Max} close to this study. However, Bucher et al. found differences between strength levels and experience that we did not identify in our study. In this sense, CF practitioners with high strength levels might have shown higher heart rates than LS ones during both WODs but our HS participants are more experienced than the LS. Therefore, our results agree with another current study [46] which supports that there exists no relationship between participants' expertise and heart rate responses, suggesting that the CF training concept provides a progressive cardiovascular load increase characterized by high intensity, which reached values above 90% of HR_{Max} (specifically in the WOD), regardless of experience level.

In spite of the fact that neuromuscular and physiological variables did not show any differences between WODs or strength levels, our results might support that standardized and relativized workouts only had different outcomes in fatigue perception and performance in both groups. For these reasons, this study may provide evidence of the need to individualize weight lifted in CF as similar physiological effects are achieved with a lower volume of repetition and adjusted effort perception, especially for HS participants.

There are a few limitations to this study. First, the authors did not perform an incremental exhaustion test on the participants to determine their HR_{Max}, but they used the theoretical HR_{Max}. Second, they conducted a push press movement test instead of the more common back squat 1RM one to classify the bodyweight-1RM ratio.

CONCLUSION

Relativized intensity AMRAPs in CF provide a similar physiological response to that in standardized WODs regardless of the participants' strength level but homogenizes the perceived effort and total volume. Future studies should delve into the long-term effect of training in relativized and standardized WODs for HS participants since they were mainly affected by relativized load.

PRACTICAL APLICATIONS

Coaches should assess the strength and skill level of their participants in the CF boxes to individualize workouts so as to achieve the desired outcomes when prescribing them. Although in this regimen's competitions participants perform WODs with the same load for all competitors, individualizing training and using relative loads may help elicit the desired high-intensity acute response to the training stimulus.

Conflict of interest

The authors declare that they have no conflict of interest

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APPENDIX 3.

Note: This study was published.

8.3 STUDY 3: Oliver-López, A., Brandt, T., Schmidt, A., & Sabido, R. (2025). Prediction of thruster maximum load using clean and jerk one-repetition maximum: influence of gender and experience in CrossFit athletes. *The Journal of sports medicine and physical fitness*, *65*(8), 1030–1038. https://doi.org/10.23736/S0022-4707.25.16660-7

8. Chapter 8: Appendices. Appendix 3

Study 3: Prediction of Thruster maximum load with Clean and Jerk 1RM

ABSTRACT

BACKGROUND: Strength coaches use the repetition maximum (1RM) of key movements to predict the load for derivate exercises in sports like weightlifting or CrossFit (CF). Although this is a fundamental CF exercise, no prediction equations have been established for the thruster (TH). Therefore, this study aimed to determine the relationship between the clean and jerk (CJ) and TH 1RM in CF athletes and analyse the influence of gender and experience. METHODS: Seventy-three participants (40 male; 33 female; age: 30.1±8.2 years) with ≥3 months of CF experience were enrolled in this study. The CJ and TH 1RM were tested in 2 separate sessions. Additionally, anthropometric data and CF experience were taken. Linear correlation and regression analyses were applied to investigate the relationship between both exercises. For further analyses, participants were subdivided by gender and CF-experience [men and women experienced (EM;EW)]: ≥24 months CF-training, and [men and women beginners (BM;BW)]: <24 months CF-training. RESULTS: Very high significant ($p<.001$) correlations were found between CJ and TH ($r=.98$) across all participants and for EM ($r=.98$), BM ($r=.96$), EW ($r=.95$), and BW ($r=.90$). Similarly, the coefficient of determination was high to very high for all participants ($R^2=.97$) and for all the groups; EM ($R^2=.97$), BM ($R^2=.91$), EW ($R^2=.91$), and BW ($R^2=.82$). Prediction equations were calculated for EM (TH=0.81*CJ+9.98), BM (TH=0.80*CJ+10.23), EW (TH=0.63*CJ+17.39), and BW (TH=0.96*CJ+(-2.21). CONCLUSIONS: This is the first study on CF athletes that guides prescribing individualised loads in the TH which is essential to induce appropriate training stimuli to achieve the desired adaptions.

Key words: strength training, resistance exercise, load estimates, prediction equation.

INTRODUCTION

The fundamentals of strength training, such as specificity, overload, reversibility, and individualisation, have been developed by many scientists with the aim of structuring a guide to improve the fitness and performance of athletes (Enoka, 2008; Feigenbaum & Pollock, 1997; Verkhoshansky, Y., & Siff, 2009). Programming is a technique used to control these fundamentals of strength training in order to improve strength and power development, and peak performance can be achieved by managing these training variables through appropriate periodisation (Graham, 2002; Lorenz & Morrison, 2015; Stone et al., 2021). Consequently, based on the fundamental of individualisation, coaches often prescribe loads based on the maximal strength values of their athletes by modifying the intensity of the effort required according to the stage of their periodisation (García Valverde et al., 2024a).

The one repetition maximum (1RM) test has long been considered the benchmark for determining the optimal intensity prescribed for training and for assessing the strength of athletes. 1RM testing can be an accurate method of assessing strength regardless of the physical condition and training status of the participants (García Valverde et al., 2024a; Grgic et al., 2020; Jawade, 2021; Lindberg, K., Solberg, P., Bjørnsen, T., Helland, C., Rønnestad, B., Frank, M. T., ... & Paulsen, 2022). Exercise prescription during resistance training programs is usually based on the participants' maximal strength values but it is uncommon and impractical for coaches and athletes to test the 1RM of numerous auxiliary exercises. Nevertheless, coaches often use references from basic strength movements and apply formulas prescribed in the literature to estimate the optimal intensity in auxiliary exercises or weightlifting derivatives (Ebben, W. P., Feldmann, C. R., Dayne, A., Mitsche, D., Chmielewski, L. M., Alexander, P., & Knetgzer, 2008; Lucero et al., 2019).

Concerning weightlifting movements, the clean and jerk (CJ) is widely used in training programmes, not only by weightlifting specialists but also by CrossFit (CF) coaches (Meier et al., 2021). A major advantage of this movement over the snatch is that it does not require an overhead barbell movement in a deep squat position, and therefore it does not impose as much mobility on the participants (Mohamad et al., 2021). In addition, sports researchers have found strong relationships between the CJ or its derivatives and some strength movements. So, while Soriano et al. (M. A. Soriano, Jimenez-Ormeno, et al., 2022) found a relationship in weightlifters between the 1RM of the back squat and overhead press and the prediction of maximum performance in split jerk (R^2=0.85; R^2=0.94), other studies found lower predictions for the influence of the 1RM back squat in the snatch (R^2=0.76) and clean and jerk (R^2=0.84) in CF athletes (Meier et al., 2021). Even so, the estimates for weightlifters may not be extrapolated to other athletes for whom the technical skill may be lower, and coaches must also bear in mind variables such as athletes' experience, gender, or anthropometric characteristics (Cooke, D. M., Haischer, M. H., Carzoli, J. P., Bazyler, C. D., Johnson, T. K., Varieur, R., ... & Zourdos, 2019; Thomas, G. A., Kraemer, W. J., Spiering, B. A., Volek, J. S., Anderson, J. M., & Maresh, 2016).

Regarding weightlifting movements, different derived movements have emerged due to new training disciplines in the fitness field. One such discipline CF, a training modality that emphasises multi-joint functional movements, elicits greater muscle recruitment and is characterised by a combination of gymnastics, endurance, and a mix of basic strength and weightlifting exercises (Feito, Heinrich, et al., 2018; Schlie et al., 2023). In this training modality, one of the barbell strength movements that athletes repeat more frequently in their training sessions is the thruster (TH). The TH is a new movement coined by CF, first introduced on their website in 2001 as part of a training routine; it is now the third most repeated movement on CF

Open Workouts, after double under and muscle up, being the most frequent barbell weight movement (CrossFit, 2001). In the TH, athletes start in the front squat position and perform a front squat below parallel followed by a push press (Fernández-Fernández et al., 2015; Maté-Muñoz, J. L., Budurin, M., González-Lozano, S., Heredia-Elvar, J. R., Cañuelo-Márquez, A. M., Barba-Ruiz, M., ... & García-Fernández, 2022).

While the 1RM of the TH is not one of the best-known maximum repetitions among athletes, and we have not found any studies that relate its value to that of other movements, the value of the clean and jerk (CJ) is usually known because it is one of the main movements in weightlifting and training sessions for different sports to improve the performance of athletes (Comfort et al., 2023). Furthermore, the demands on lower body strength in the squat and upper body strength in the overhead press are similar to those observed in the CJ and TH. Some authors have also described the kinematic patterns of these movements. For example, in the first part of the CJ, the bar moves up from the floor and lands on its shoulders, supported by the arms, known as the front rack position, a movement also performed in the TH to start the sequence. The difference would come in the overhead movement, completing a front squat into an overhead press with the hips extended and elbows locked at the end of the movement for TH, concerning CJ where athletes push themselves into just a quarter dip & drive the hip before extending the lower limb joints while the bar is in the front rack position to land in an overhead split jerk (Dexheimer et al., 2020; Lazar, 2022).

Thus, the aim of this study was to determine the relationships between 1RM of the CJ and TH in CF athletes. A further aim of this study was to investigate the magnitude of these relationships as a function of the gender or experience of the participants in CF training and to establish prediction equations. It was hypothesised that TH performance could be predicted from CJ performance in men and women, but the strength of the correlation may be lower in participants with less than two years' experience, regardless of gender.

MATERIALS AND METHODS

Participants

To ensure enough statistical power, the optimal sample size was determined prior to the study using G*Power 3.1 (Erdfelder et al., 2009). Based on Cohen's f large effect size (Cohen, 1988b), the a priori sample size analysis set alpha at 0.05 and statistical power at 0.8 for both correlation bivariate and regression models. We expected a medium effect size in the correlation and regression model ($r = 0.30$; $f2 = 0.15$, respectively), giving us a required sample size of 67 or 68 participants. Seventy-three participants (40 male, 33 female) were recruited for this study (Table I). Subjects were members of CF boxes with a minimum of three months' experience in the discipline who attended CF at least three training lessons per week. Participants were included who met the following criteria: (i) aged 18 or older; (ii) willing to attend two 1RM tests; (iii) willing to avoid strength training 48 hours before testing; and (iv) willing to maintain their habitual nutrition during the study. Acute or chronic health conditions (cardiovascular, respiratory, severe musculoskeletal, or metabolic disease), and taking drugs or supplements to enhance performance (e.g. benzodiazepine or caffeine) were exclusion factors. Participants were sorted according to gender and experience in CF training with the following criteria: those with more than 24 months' experience were assigned to the experienced group (experienced men, EM; experienced women, EW), and participants with less than 24 months' experience were assigned to the beginner groups for men (BM) and women (BW) in the analysis of the present study

(Durkalec-michalski et al., 2019; Feito, Giardina, et al., 2018b; Mangine et al., 2020b; Menargues-Ramírez et al., 2022; Sprey et al., 2016). All participants signed a consent form before starting the study. Ethical approval was provided following the guidelines of the Declaration of Helsinki and the research was conducted following the research committee of the Miguel Hernández University (Ethics Committee ID: 230210121042).

Table I.— Athletes' descriptive characteristics
(40 male and 33 female; age: 30.1±8.2 years; height: 172.1±0.1 cm; body weight: 74.1±15.8 kg; CF training experience: 45.2 ±34.9 months)

Variable	/N/	Group	Mean±SD	Range	p-value	ES
Age (y)	/24/	EM	35.29 ± 8.13	[24-59]		
	/16/	BM	29.56 ± 7.77*	[18-44]	.03	0.72
	/17/	EW	32.41 ± 8.08	[24-52]		
	/16/	BW	29.06 ± 7.84	[22-54]	.24	0.42
Height (cm)		EM	175.87 ± 8.49	[163-190]		
		BM	177.81 ± 2.17	[174-181]	.42	0.31
		EW	164.58 ± 5.35	[156-177]		
		BW	167.81 ± 5.38	[158-176]	.09	0.59
Body Weight (kg)		EM	83.67 ± 18.15	[52-150]		
		BM	81.88 ± 9.83	[65-105]	.72	0.12
		EW	60.27 ± 5.76	[51-70]		
		BW	66.88 ± 9.13*	[50.5-80]	.02	0.87
CF Exp (months)		EM	72.13 ± 33.45	[29-144]		
		BM	14.56 ± 7.17*	[3-24]	<.001	2.38
		EW	63.29 ± 24.35	[27-103]		
		BW	15.94 ± 5.91*	[6-24]	<.001	2.67
1RM Thruster (kg)		EM	89.63 ± 15.44	[60-120]		
		BM	73.13 ± 13.23*	[54-100]	<.001	1.15
		EW	54.59 ± 6.45	[45-67]		
		BW	50.19 ± 9.17	[32-65]	.12	0.56
1RM Clean & Jerk (kg)		EM	98.29 ± 18.69	[62-135]		
		BM	78.25 ± 15.72*	[55-108]	<.001	1.16
		EW	59 ± 9.74	[42-74]		
		BW	54.63 ± 8.63	[40-68]	.18	0.47

*p < .05; ES=Effect size; Experienced men and experienced women groups (EM and EW, respectively) ≤ 24 months Beginners men and beginners women groups (BM and BW, respectively) > 24 months of CrossFit experience (CF Exp)

Study Design

A cross-sectional descriptive study was designed. Participants attended their CF boxes twice to perform the 1RM in the CJ and TH movements. Participants signed the consent form and then descriptive data, like height and weight, were collected.

This was followed by a five-minute bicycle ergometer (Concept2, Vermont, United States) warm-up at an easy pace, and a specific barbell warm-up depending on CJ or TH 1RM session day. On the day of the CJ, male athletes with an unloaded Olympic barbell of 20 Kg and female athletes with 15 Kg, performed the following barbell cycling sequence for two sets with a minute rest separated: five deadlifts, five pull cleans, five hang power cleans, ten front rack shoulders rotations, and three split jerks. On the day of the TH, the sequence with the barbell was: five hang power cleans, ten front rack shoulder rotations, three push presses, three front squats and five thrusters. After the warm-up, the participants rested for three minutes before starting the maximal test.

For this main part of the session, the protocol of Baechle and Earle (Baechle, T. R., & Earle, 2002) presented in Figure 1 was carried out to perform at maximum weight in the two movements. For both sessions, participants performed the 1RM protocols at the same time of day. The two 1RM assessments were separated by 72 hours to guarantee rest between both sessions and participants had verbal encouragement from partners and coaches (Belkhiria et al., 2018; Engel et al., 2019). Furthermore, coaches supervised the participants' movements to ensure their safety and to record the maximum weight for each athlete in the two barbell movements, CJ and TH.

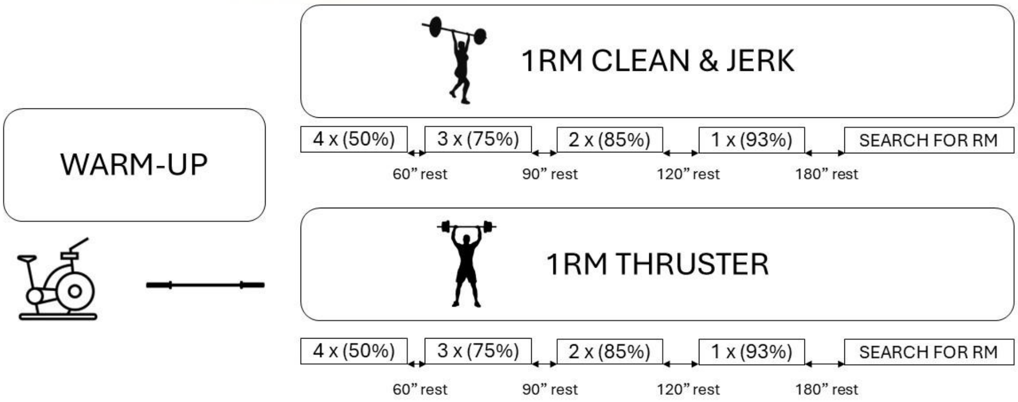


Figure 1. Protocol performed for the incremental tests to assess the 1RM

Procedures

Previously during both sessions, the coaches spoke about the objective of the day's training and how to increase the maximum weight in the CJ or TH, to reach the goal of a new personal record. To prepare for the 1RM session, the two unloaded sets of barbell warm-up and the first set of four repetitions at 50% of 1RM, were performed for the participants. In addition, considering that three months of experience in this discipline was one of the requirements for enrolling in this study, the coaches attested to the researchers that the individuals had performed the two exercises in previous sessions.

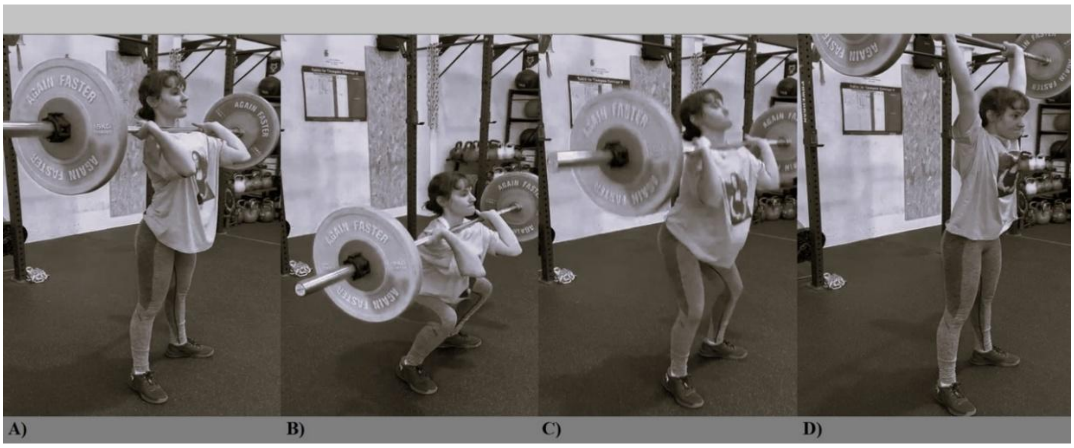
Clean and Jerk

The requirements for rating the CJ movement as a good repetition were (i) starting with the bar on the floor; (ii) reaching an intermediate clean phase on the shoulders; (iii) being able to perform the clean catch from a half squat or a full squat; (iv) performing a displacement with the feet in the sagittal plane and in opposite directions; (v) and remaining still at the end of the movement with the elbows extended and feet parallel (Bob, 1998). The criteria for invalid attempts were the contact of the elbows with the knees in the catch position of the clean phase, the use of rebounds of the barbell with shoulders to perform the split jerk, and the participants´ displacement with the barbell in an overhead position before dropping it.

Thruster

In order to give the movement of TH as a good repetition, the requirements were (i) starting with the barbell completely on the floor; (ii) carrying the barbell on the shoulders; (iii) performing the phase of the front squat (Gullett, J. C., Tillman, M. D., Gutierrez, G. M., & Chow, 2008) with a full squat; (iv) performing a push press (C. Bishop et al., 2018) without any stop; and (v) staying still with the elbows extended at the end of the movement (Figure 2). Moreover, the criteria for invalidating a new attempt were the contact of the elbows with the knees during the front squat phase of the TH and keeping moving during the phase overhead without a full body extension before dropping the barbell.

Figure 2. Thruster motion sequence



Note: A) Front rack position; B) Deep position of the Front Squat; C) Transition between the concentric phase of Front Squat and Push Press; and D) End of Thruster movement in Overhead position

Statistical Analysis

Firstly, the Shapiro-Wilk test was used to confirm a normal distribution of the data. Secondly, a linear correlation was conducted to explore the relationships between the 1RM of the CJ and maximal TH performance in all participants. Pearson's correlation coefficients (r) with 95% confidence interval (CI) were calculated in both variables. This coefficient result was interpreted using modified Cohen's criteria: very small (<.10), small (.10-.29), moderate (.30-.49), large (.50-.69), very large (.70-.89), or extremely large (>.90) ´(WG Hopkins, 2002). Thereafter, a regression analysis was carried out to elucidate how much of the variation in CJ would explain the TH maximum repetition. For the second objective, multiple correlation and regression analyses were performed, participants being classified according to (i) gender (ii) and level of experience. An a priori alpha level of $p \leq .05$ was set. Furthermore, analysis was complemented by a statistical process of the machine learning group: specifically, cluster analysis (CA) was applied to identify different groups related to weightlifting performance according to their anthropometric characteristics. A set of four variables (TH performance, CJ performance, height, and body weight) were included and analysed. For the clustering analysis, the model was given the freedom to perform up to ten clusters based on the relationship between these variables. These variables have previously been related to weightlifting performance and specifically to CF performance (Ferrari et al., 2022; Keogh, Justin W., Hume, Patria A., Pearson, Simon N., Mellow, 2009; Vidal Pérez et al., 2021). All statistical tests were performed with the JASP software (v0.17.1.0).

Data availability

The data associated with the paper are not publicly available but are available from the corresponding author on reasonable request.

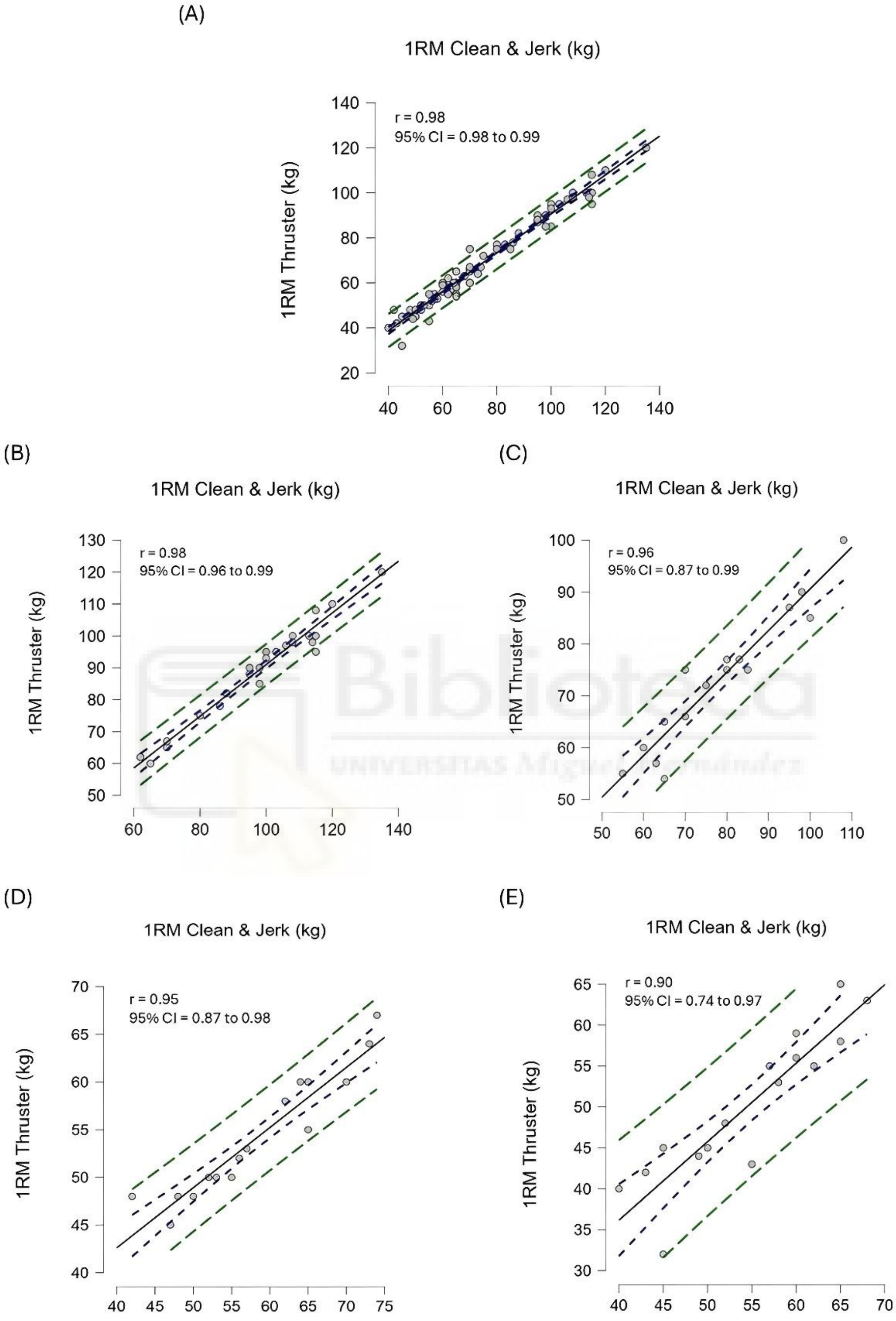
RESULTS

As displayed in Figure 3, these significant correlations indicated that the 1RM in the TH was strongly related to the CJ performance (r=.98; p<.001). Subdividing participants by gender and training experience also revealed extremely high correlations for EM (r=.98; p<.001), BM (r=.96; p<.001), EW (r=.95; p<.001), and BW (r=.90; p<.001).

The coefficient of determination (Figure 4) was high for all participants (R^2=.97; 95%CI=0.83-0.9; p<.001), as well as in the model for EM (R^2=.96; 95%CI=0.74-0.88; p<.001) and BM (R^2=.91; 95%CI=0.66-0.95; p<.001). Furthermore, the regression model for EW was high (R^2=.91; 95%CI=0.52-0.74; p<.001) but showed a lower coefficient of determination for BW (R^2=.82; 95%CI=0.7-1.22; p<.001). The predictive equations calculated from the constant (Y-intercept) of the regression model in each group are presented in Figure 4.

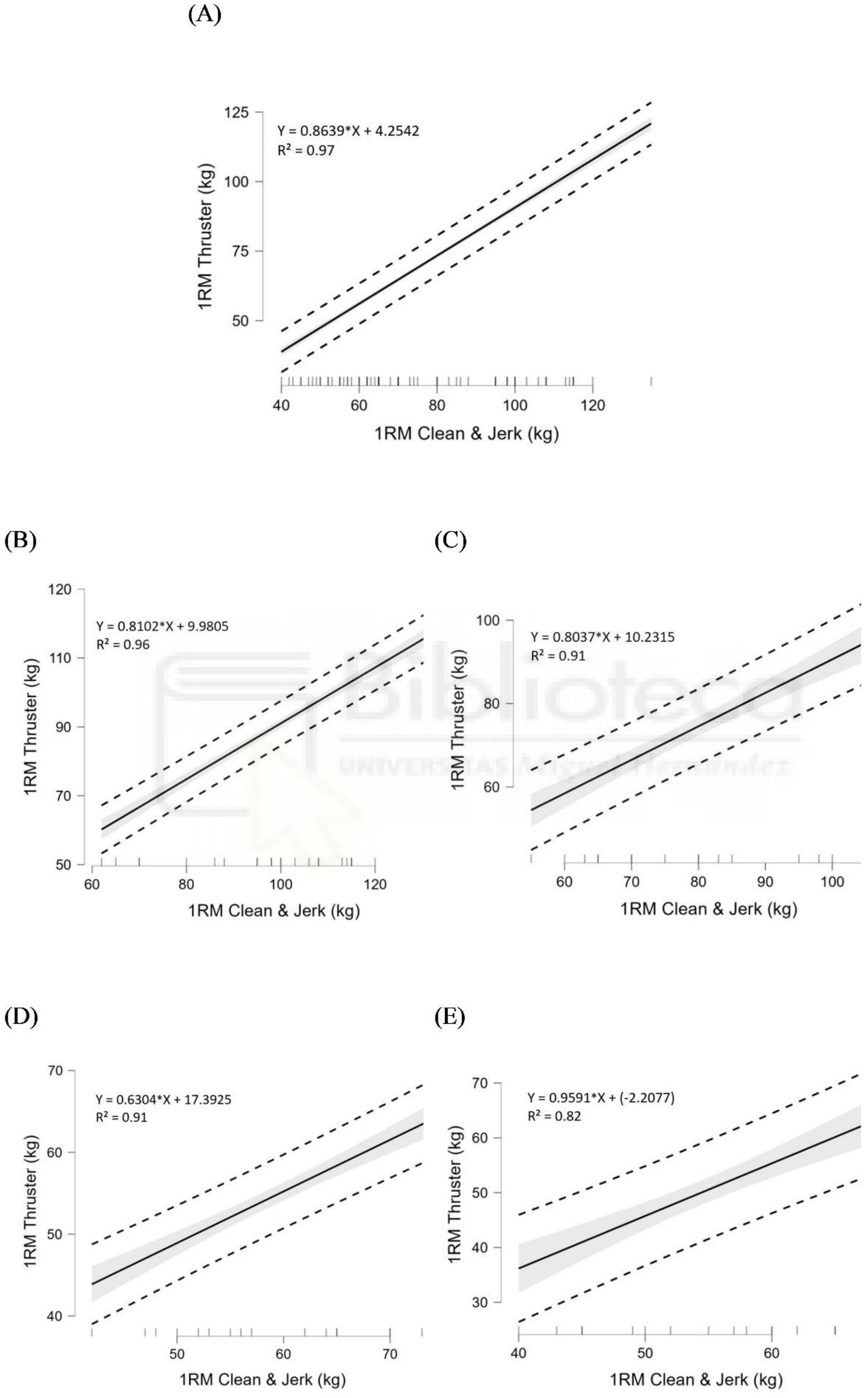
The clustering analysis found four groups in the function of the relationship between 1RM in TH, 1RM in CJ, height, and body weight of participants (Figure 5).

Figure 3.— Correlation plot between 1RM of the TH and the 1RM of the CJ



Note: A) All participants sorted by different groups in order of gender and experience: (B) Experienced men; (C) Beginners men; (D) Experienced women; (E) Beginners women

Figure 4. Marginal effect plot of the regression lineal model



Note: Actual and predicted values of the 1RM during the TH of all participants (A) and sorted by different groups in order of gender and experience: (B) Experienced men; (C) Beginners men; (D) Experienced women; (E) Beginners women

DISCUSSION

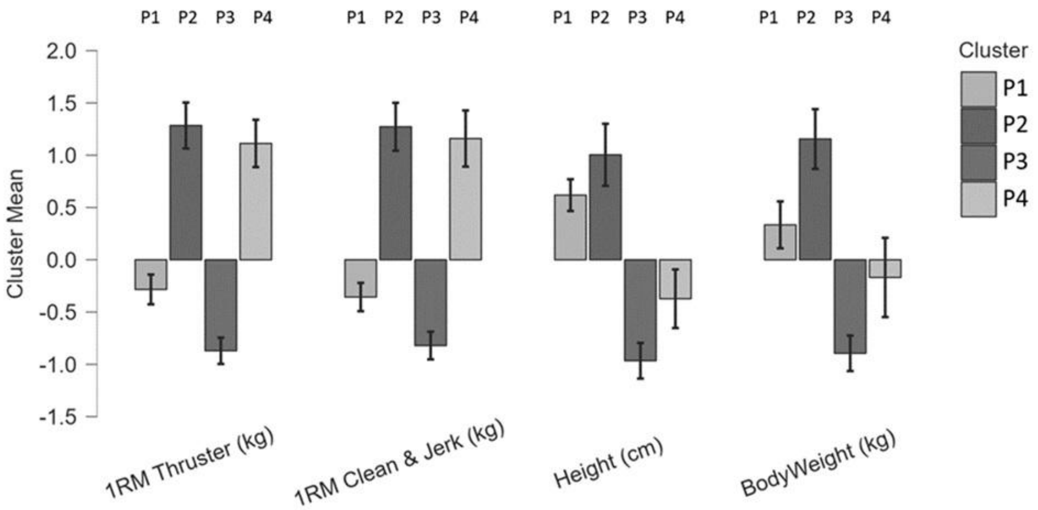
The present study aimed to determine the relationship between performance in the CJ and TH movements in CF athletes and to analyse the influence of gender and experience on this model. The main finding was the strong relationship between the CJ and TH 1RM. A novel finding of this study was the ability to predict the TH performance from the CJ 1RM, considering the gender and experience of CF athletes. This is the first study to establish a relationship between the TH movement and the performance in weightlifting. These findings are relevant for CF coaches when prescribing the training load of TH, considering their benchmark in CJ movement.

Our results indicated a significant correlation between the maximum repetition in TH and CJ in all crossfitters. In the same way, when participants were sorted by gender and training experience level, strong correlations were found. These findings are in line with other studies involving competitive weightlifters concerning performance in the CJ and back squat (r=.91, p<.01)´ (Lucero et al., 2019; Shetty AB, 1990). These results support the idea that there is a high correlation between general strength measures of the hip and knee extensors during the squat and the weightlifting performance. The results with weightlifters in another study agree with our findings for experienced athletes of both genders for squat and split jerk (r=.91, p<.01; r=.89, p<.01, respectively), but present a weaker relationship for upper body movement between overhead press and split jerk (r=.75, p<.01; r=.72, p<.01, respectively) (M. A. Soriano, Jimenez-Ormeno, et al., 2022). This fact could be explained by the overhead press being a strict movement that elicits shoulder muscles, while in the TH the athletes perform a coordinated movement of the lower and upper body to push the barbell overhead.

Our results for crossfitters are consistent with the results of other studies that found a high level of variance in CJ performance in the back squat (R^2=.84); the results confirm the important role of the 1RM squat in maximal performance of the CJ, which is one of the movements included in many CF events and competitions (Meier et al., 2021). Butcher et al. (S. Butcher et al., 2015b) found similar results for beginner crossfitters, demonstrating the relevance of maximal squat strength and CJ performance (R^2=0.77, p<.01). Besides, this supports the suggestion of Stone et al. (Stone et al., 2005) that the main contribution of the back squat to weightlifting may be to provide the overload or conditioning drive needed to increase the percentage of 1RM in weightlifting movements.

The coefficient of determination was high for men crossfitters, as well as for experienced women, showing a higher coefficient of determination than the beginner women. Similar results were found for upper body strength movements, with lower correlation between the push press and the split jerk in women than in men with weightlifting experience (r=.86, p<.01; r=.64, p<.05, respectively) (M. A. Soriano, García-Ramos, et al., 2022). The current authors attribute this gender difference to higher absolute strength values in men, which could have a significant role in consistency in 1RM performance. In the case of women, as lower absolute strength levels were observed, individual technical mastery has greater relevance for consistency in 1RM performance. Regarding the experience level, studies with experienced lifters (Lucero et al., 2019) have shown a statistically higher level of efficiency in their weightlifting performance relative to those who are less experienced (p<.01); these results are consistent with our finding that the accuracy of the prediction depends on participants' experience.

Figure 5. Cluster Mean Plot



Note: In the sample emerged four groups with the following characteristics: P1 (n = 21) Low level of strength with height and body weight above the mean; P2 (n = 16) High level of strength with height and body weight above the mean; P3 (n = 27) Low level of strength with height and body weight below the mean; P4 (n = 8) High level of strength with height and body weight below the mean

Lastly, our findings with cluster analysis revealed four participant groups (P1–P4) in terms of their anthropometric characteristics, and these had some relationship with maximum performance in the TH and CJ (Figure 5). These findings are consistent with those authors who have emphasised the relationship between height and muscle cross-sectional area (Ford et al., 2000). Other studies propose that height is a conditioning factor that may be related to the number of fibers and the cross-section of the muscle groups (Handsfield et al., 2014): as elite weightlifters have reached maximal or near maximal muscle fiber size (i.e., muscle cross-sectional area), then the final number of muscle fibers should be strongly correlated with height. Thus, height in elite weightlifters should reflect muscle cross-sectional area, which, in turn, is strongly correlated with increased performance in weightlifting to maximum strength (36). However, one of the cluster analysis groups (P4) disagreed with this trend: these were short lifters with great performance in weightlifting, which may be due to the fact that shorter height and limb lengths of weightlifters provide mechanical advantages when lifting heavy loads by reducing the mechanical torque (Storey & Smith, 2012). Our results fit with both lines of argument, finding taller participants with great performance in TH and CJ and some shorter participants with great performance in both movements. These groups may appear due to the considerable number of crossfitters measured in our study.

CONCLUSIONS

The findings of this study provide a benchmark for the maximum load in the TH movement with reference to the CJ and establish different prediction equations considering gender and experience level. This is of high relevance since the TH is the most repeated barbell movement in official CF competitions. Despite this finding, one major limitation of the study that must be highlighted is the variability of CF athletes in terms of height, body weight, and relative strength, which may be relevant variables if the participants lift more or less weight in the exercises analysed. Another limitation is the absence of test-retest measures to assess the reliability of both 1RMs in the study participants.

The main application of the present study is that the TH performance can be predicted from the CJ performance. Indeed, the multiple regression analysis for all participants indicates that TH performance is representative in up to 97 percent of all cases (Figure 4A). Furthermore, the following equations are provided for athletes: experienced men (TH = 1RM=0.8102*CJ+9.9805), beginner men (TH 1RM performance = 0.8037*CJ + 10.2315), experienced women (TH 1RM=0.6304*CJ+17.3925), and beginner women (TH 1RM=0.9591*CJ+[-2.2077]). This finding is essential for coaches to prescribe individualised loads in the TH movement and to help each crossfitter achieve the desired adaptations with periodised CF programs. Furthermore, these formulas depending on gender and experience could orient the intensity of the training to an individualised barbell weight with accuracy and fast estimation knowing the CJ weight, and advantage over the TH movement used frequently during WODs and sometimes without weight references of maximum loads. In summary, this provides a tool for prescribing and manipulating the intensity of training in TH days individually and optimised for athletes.

Finally, to adjust the loads more optimally for crossfitters in frequent barbell movements, future research is recommended to include other CF strength movements in which it is not common to perform 1RM for maximum strength, and to relativise training loads according to individual strength capacity.

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APPENDIX 4.

Note: This study is in the review process.

8.4 STUDY 4: Oliver-López, A., Sabido, R., Brandt, T., & Schmidt, A. (2025). *Optimizing CrossFit® Performance: Individualized Load Prescription vs. Standardized Rx Weights.* Manuscript under review.

8. Chapter 8: Appendices. Appendix 4

Study 4: Optimizing CrossFit® Performance: Individualized Load Prescription vs. Standardized Rx Weights

ABSTRACT

Purpose: This study aimed to compare the effects of relativized barbell loads (% of 1RM) versus standardized Rx loads on CrossFit® (CF) performance, strength adaptations, physiological responses, and perceived effort.

Methods: Twenty-two experienced CF athletes (12 males, 10 females) were randomly assigned to a standardized load (SL) or relativized load (RL) group. Both groups completed an eight-week CF training program with benchmark workouts. Performance was assessed using the Tibana Test (TT), maximal strength through 1RM testing (back squat, clean, and clean and jerk), and neuromuscular performance via countermovement jump (CMJ). Cardiopulmonary responses (VO_2peak, VO_2mean, heart rate, and blood lactate) and perceived effort (Borg CR-10) were also evaluated.

Results: RL participants showed significantly greater improvements in TT performance ($p = 0.009$, 95% CI [5.2, 10.5]) and strength gains in back squat ($p = 0.005$, 95% CI [3.1, 8.6]) and clean ($p = 0.027$, 95% CI [1.2, 5.7]) compared to the SL. No significant differences were found in clean and jerk performance or CMJ height. Cardiopulmonary responses were similar between groups, indicating comparable physiological stress. RL participants reported significantly lower perceived exertion ($p < 0.001$, 95% CI [6.3, 9.8]), suggesting better load management and recovery.

Conclusions: Individualized loads based on 1RM enhance CF performance and strength adaptations without increasing physiological stress, promoting more efficient training and reduced fatigue.

Key Words: high-intensity functional training, individualization, adaptation, performance.

INTRODUCTION

CrossFit® (CF) is a training modality categorized as high-intensity functional training (HIFT), high-intensity power training, or an extreme conditioning program (Dominski et al., 2022). An important component of CF training is the "workout of the day" (WOD), which demands high-intensity cardiovascular and strength efforts. It blends multiple disciplines, including weightlifting and bodyweight exercises, while also requiring the capacity to complete various tasks as quickly as possible (3). The worldwide spread of CF over the last years has brought together a heterogeneous group of practitioners with diverse characteristics, and some researchers have demonstrated the effects of this training on their physiological and psychological responses (Oliver-Lopez et al., 2022; Schlie et al., 2023). Apart from these studies, some CF health-based interventions have been carried out to inform the adaptations in different populations, such as overweight adults (Heinrich et al., 2014), young students (Garst et al., 2020), diabetic patients (Nieuwoudt et al., 2017), or sedentary workers (Brandt et al., 2024), with positive benefits in body composition, health-related fitness, insulin sensitivity, oxygen uptake (VO_2max), or adherence.

This diversity is also reflected within CF gyms, known as "boxes," athletes with a high level of strength and who aspire to be competitive share training with participants whose goal is to create good habits and improve their health (Mangine et al., 2020b). A common example is when coaches prescribe standard workouts, like the Hero WODs, characterized by standardized movements and fixed intensity barbell weights for males or females, with "scaled" versions available to simplify movements or reduce weight in an attempt to adapt the workouts to all audiences (Brandt et al., 2023). However, scaled WODs have limited individualization due to the lack of adaptive training loads that meet the needs of every participant. This lack of individualization may hinder the effectiveness of the training, particularly in terms of promoting rapid progression and reducing the risk of injury, which is an essential tenet of effective training (Oliver-López et al., 2023).

Individualizing load in CF programs has become challenging due to the mixture of gymnastics, endurance, and strength training (Sharp et al., 2022). Nevertheless, strength training has been historically assessed and prescribed by one-repetition maximum (1RM), considered the gold standard for training prescription and athlete strength assessment, regardless of the previous resistance training experience, sex, and age (García Valverde et al., 2024b). In addition, the CF sessions sometimes have a main part after the warm-up in which participants perform a strength or weightlifting movement, such as the back squat (BS), the clean (C), or the clean and jerk (CJ), where the intensity is prescribed by the percentage of the 1RM previously assessed in the preceding sessions. However, as previously noted, WODs prescribe a standard barbell weight based on gender for Rx athletes or a scaled version with a reduced weight.

Currently, only one study in the literature analyzes the acute responses to a WOD when comparing Rx standardized loads to relativized loads based on 1RM (Oliver-López et al., 2023). This study was carried out using 50 kg for males and 35 kg for females in CJ during the standardized WOD, and 75% of 1RM in the push press movement for CJ in the relativized WOD. The results showed that performance in CF athletes with high and low strength levels changed with relativized loads to a more homogeneous number of repetitions between athletes. Moreover, the effects expressed in blood lactate [La], countermovement jump height (CMJ), heart rate (HR), and perceived effort (RPE) had a greater impact in the group of high-strength athletes than in the standardized load WOD. Nonetheless, there are no studies on CF training periodization in which the Hero WODs with their Rx loads in barbell weights are used for one group: standardized load

(SL), in parallel with another group using individualized loads according to their 1RM in the same training sessions with the same WODs, relativized load (RL). Likewise, to check the general adaptations, including CF performance, maximum strength, and jump height, well-specific adaptations, such as neuromuscular, physiological, and perceptual responses during the muscular endurance WOD called Tibana Test (TT), (Tibana et al., 2021b) are evaluated before and after the intervention.

Therefore, this study aimed to examine changes in TT performance, 1RM, CMJ height, physiological adaptations (VO_2, HR, and [La]), and perceived effort in the SL and RL groups following a CF intervention. We hypothesized that the RL group would show greater improvement in TT repetitions and enhance 1RM and CMJ height. Furthermore, our second hypothesis was that both groups would exhibit efficient physiological responses in TT assessment.

METHODS

Overview of the experimental design

This study followed an experimental intervention with two groups, SL and RL, depending on a fixed or individualized load during CF workouts. This intervention was performed from May to July 2024 in two CF boxes in Spain, and data collection was taken in the laboratory. The study was integrated into the periodization of both CF boxes to avoid disturbing the progress of the participants and the social context of the training box they attend every day. The groups were measured in the same manner at the start of the intervention, at the middle to assess their maximum repetition, and at the end of the study.

Before the participants' enrolment, we informed them about the protocol and potential risks, and they provided informed written consent. We developed this study following the guidelines of the Declaration of Helsinki and conducted it following the research committee of Miguel Hernández University (Ethics Committee ID: 230210121042).

Subjects

The preliminary examination of the sample size was estimated based on a previous systematic review in which different chronic physiological responses after CF training were studied (Oliver-Lopez et al., 2022). In addition, to satisfy the statistical power criterion for an ANOVA (repeated measures with interaction effects), G*Power Version 3.1.9.6 software was used with a priori sample size analysis based on a large effect size of 0.4, partial η^2 0.14, setting the power statistic at 0.8, and alpha at 0.05 for a two-sided test, yielding a requirement of 16 participants for the present study (Faul et al., 2007).

Twenty-five participants were recruited at the start of this intervention, but three participants dropped out during its current development. One participant left the intervention due to personal circumstances, and the other two subjects withdrew due to knee and lower back pain and discomfort. This study reported a prevalence of 8% of injuries. Consequently, 22 participants (12 males and 10 females) completed the CF training (Table 1).

Table 1. Descriptive Statistics of the 22 final participants at baseline.

	All Participants (n = 22)	Standardized Load Group (n = 10)	Relativized Load Group (n = 12)
Male (n)	12	5	7
Female (n)	10	5	5
Age (y)	38.1 ± 7.8	36.8 ± 8.5	39.3 ± 7.4
Height (cm)	171.2 ± 8.9	171.6 ± 10.4	170.9 ± 8.1
Weight (kg)	73.8 ± 11.3	73.8 ± 9.5	73.8 ± 12.9
Ratio[1]	1.4 ± 0.2	1.4 ± 0.3	1.4 ± 0.2
CF experience (months)	77.5 ± 36.3	82.9 ± 36.8	73.0 ± 36.9

[1]maximal weight lifted in back squat divided by body weight.

Participants enrolled in the intervention met different inclusion criteria, which were checked after an interview through a questionnaire. These criteria were having attended CF lessons at least 12 months previously, reaching minimum requirements in gymnastic movements (performing at least three repetitions of pull-ups and five repetitions of ring dips), and lifting standardized weights in a weightlifting overhead movement (raising more than 70 kg for male and 47.5 kg for female in the push jerk). Apart from these conditions, exclusion criteria were: i) using performance-enhancing drugs; ii) being pregnant; iii) having a cardiovascular, metabolic, or respiratory pathology; and iv) having injuries that could affect participants' health during the study (e.g., rotator cuff strain or recurrent low back pain).

During the intervention, participants refrained from exercise training outside our CF sessions and continued their normal dietary habits before the study. In addition, two groups of participants were defined according to the barbell weight prescribed during the training sessions: i) the group with the standardized load (SL) determined for men and women in the benchmark WODs, and ii) the group with the relativized load (RL) calculated barbell load by the percentage of the 1RM of three barbell movements 10. The participants were grouped as homogeneously as possible based on their strength ratio (maximal weight lifted in back squat divided by body weight) to avoid significant differences, as shown in Table 1 of the descriptive data. Moreover, SL and RL groups had an equal number of male and female participants to minimize the differences attributable to gender.

Design

Before starting the CF training, participants attended our laboratory at the start of the first week to obtain descriptive measures of height, body weight, and CF experience. In addition to the measurements above, the TT was performed with the simultaneous assessment of the cardiopulmonary variables (VO_2 and HR). During this week, and at least 72 hours apart from the laboratory measurements, participants were required to determine their 1RM for the BS, CJ, and C in their CF box, following the protocol of Baechle & Earle 15.

The CF training comprised 10 Hero WODs during the second, third, and fourth weeks, and these workouts were repeated in the sixth, seventh, and eighth weeks. Nevertheless, in the fifth week, participants only had to perform the three 1RMs to adjust barbell weight in the RL group (Figure 1). All the CF sessions had a general warm-up, a specific WOD preparation, the

CF Hero WOD, and an accessory, totalling one hour per session. A comprehensive list of CF training with all the CF training sessions can be found in Supplementary Table S1.

Figure 1. Development of the study and temporary points of the assessments.

1RM: Estimating of the maximum repetition of the back squat, the clean and jerk, and the clean / TT: Tibana Test with the measures of performance in repetitions, ventilatory exchange, Heart Rate, blood lactate, CMJ, and perceived effort.

Moreover, to adjust the weight in the barbell for the SL we followed the standard weights for males and females in Hero WODs during all the interventions, but for the RL we selected and changed the weights following the steps below:

1. A literature review established the average 1RM for experienced CF athletes in the BS, CJ, and C. Reported values for the CJ were 100, 93, and 101 kg for males and 64, 60, and 68 kg for females 16,17, leading to reference averages of 101 kg (males) and 64 kg (females). These values were used to calculate the relative intensity of loads in Hero WODs (e.g., a WOD prescribing 60 kg for males and 40 kg for females in the CJ represents approximately 60% of their 1RM).

2. Correlations and regression models were used to adjust barbell loads across different movements using the BS, CJ, and C as predictor variables 17–19. Additionally, weightlifting manuals, such as Everett's 20, provided empirical relationships for load prescription without requiring complete 1RM data (e.g., many CF workouts include thrusters, but athletes did not know their 1RM. The prediction equation developed by Oliver-López et al. 19 was used to estimate the thruster maximum load based on the CJ 1RM).

3. In WODs with more than two barbell movements, a single load was set based on the overhead movement, as it typically involves lifting less weight compared to movements originating from the floor, such as deadlifts or snatches (e.g., in the DT workout, composed of deadlifts, hang power cleans and push jerks, the intensity was prescribed using the CJ 1RM since

the push jerk determines the limiting load). Moreover, when the overhead movement differed from the kinematic of the push jerk, literature-based relationships were applied (e.g., in the “Dany” workout, composed of box jumps, push presses, and pull-ups, the push press load was set at ~88% of the split jerk, following Soriano et al. 18).

A weight calculator for the Hero WODs can be found in Supplementary Sheet 1.

Methodology

Participants completed a WOD in laboratory conditions pre- and post-CF intervention. A day before the test, participants were advised not to exercise vigorously and not to consume large amounts of alcohol or caffeine. In addition, three hours prior, they were instructed to have a healthy meal and ensure they were drinking enough water. Before the TT, all participants completed a warm-up by rowing at an easy pace for 3 minutes, followed by two sets of 10 alternating lunges, 20 shoulder taps in plank position, and 10 seconds of isometric push-up position with elbows flexed. After this part, participants completed 2 minutes of rowing at medium intensity. The WOD was an adapted version of the TT 13 composed of four As Many Repetitions As Possible (AMRAPs) where subjects had to perform the maximum number of repetitions in each AMRAP with a length of 4 minutes and had 2 minutes of passive rest after every workout. This TT workout was divided into: (round 1) 4 min AMRAP of five thrusters with two dumbbells (17.5 kg and 12.5 kg; male and female weights respectively) and five box steps (50/40 cm; male and female height respectively) with dumbbells; (round 2) 4 min AMRAP of 10 dumbbells power clean and 10 dumbbells rows; (round 3) 4 min AMRAP of 15 shoulders to overhead with dumbbells and 30 V sit-ups; and (round 4) 4 min AMRAP of 20 calories of rowing on Concept II indoor row (PM5, Vermont, USA) and 40 squat jumps. The TT and all explained measurements are shown in Figure 2.

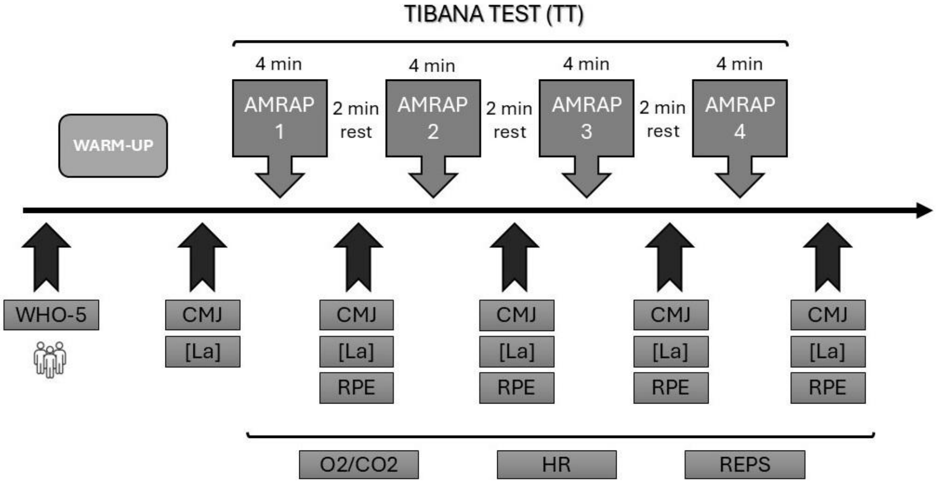

Figure 2. Temporary line of the participants' assessments during the testing days.

At the bottom of the figure are the variables WHO-5: Well-being questionnaire / CMJ: maximum height in countermovement jump / [La]: blood lactate / RPE: Perceived effort 0-10 / O2/CO2: Ventilatory exchange / HR: Heart rate as mean and maximum / REPS: Performance measure in repetitions during the test.

Performance

During the TT to guarantee that the prescribed movement, workout, and training requirements were fulfilled, each AMRAP of the test was overseen by one certified individual who had completed the CrossFit Judges Course. To score each participant's good repetitions during the assessment, the researchers had a description of all the knowledge and abilities needed, presented as though it were a competition, including movement criteria and typical errors. During all measure sessions, verbal encouragement and counting repetitions aloud were used to motivate participants to give their best effort (Mazzetti et al., 2000). The researchers collected the total score for all four AMRAPs and the repetitions for each AMRAP.

One-repetition maximum

Participants were assessed for 1RM on the BS, the CJ, and the C movements, which were performed according to Baechle & Earle guidelines (Baechle, T. R., & Earle, 2002). The time points for these measurements were before the CF intervention started, at the middle of the intervention in the fifth week, and at the end of the study in the ninth week. The three 1RMs were estimated in the same session according to the order of: the BS first, CJ second, and finally, the maximum load in the C. Finally, five minutes of rest between attempts were respected between the BS and the CJ, and the CJ and the C (Grgic et al., 2020).

Performance in CMJ

The jump height was estimated using a contact platform and Chronopic's hardware (Chronojump, Boscosystem, Barcelona, Spain). A specific warm-up of six progressive CMJs every 30 seconds was performed previously to record the best jump of three attempts at the end of the warm-up and immediately after the completion of the WOD test (Anicic et al., 2023; Harry et al., 2018). In addition, the best CMJ tested after the warm-up was used to compare neuromuscular differences between the start and end of the intervention. Participants had to keep their hands on their hips during all trials and land with their knees straight. Rebound-on landing was allowed by flexing the ankles. The first contact with the mat stopped the stopwatch and only the best jump was considered for investigation, due to potential learning effects, and to avoid greater jump performances (Petrigna et al., 2019).

Cardiopulmonary exercise testing (CPET)

Before starting the test, the face mask was worn to the participants and the last part of the warm-up was performed under this condition to familiarise them with the mask. During all the AMRAPs, ventilatory exchange was measured with a portable Breath-by-Breath system (MetaLyzer 3B-R3, CORTEX, Leipzig, Germany). Moreover, to smooth the signal in the gas analyzer, it was averaged every ten seconds after the measurements. The maximum oxygen peak (VO_2peak) and average oxygen consumption (VO_2mean) were calculated for the posterior analysis, expressed relativized by the body weight of the participants (ml/min/kg) (Glaab & Taube, 2022). Heart rate was continuously tracked using a Bluetooth heart rate belt located in the Xiphoid area and heart rate peak (HRpeak) and heart rate average (HRmean) were assessed for posterior analysis (Polar H9, Polar, Kempele, Finland). Finally, the total record of the ventilatory exchange and the heart rate was 25 minutes, including the tests' AMRAPs, the time for rest, and three minutes after the test to see the recovery phase.

Development of blood lactate

Blood lactate concentration [La] was determined by taking test strips and using a portable analyzer device (Lactate Scout Plus, EKF Diagnostics, Leipzig, Germany) in peripheral blood samples from the left earlobe. Before collection, the skin was wiped with chlorhexidine. The first two drops of blood were discarded, and the third was used for analysis. The time points of lactate sampling were one minute after warm-up (basal) and one sample at the end of the WOD test after the CMJ (Tanner et al., 2010).

Rating of perceived effort

Perceived exertion (RPE) was rated using the Borg category scale (CR-10) and all participants were familiarized with this perceived exertion scale before the start of the study (Foster et al., 2001). The CR-10 scale consists of a scale of exercise intensity defined between "rest" [0] and "maximum" [10]. Participants were asked "How hard do you think the WOD was?" at the end of each AMRAP, and 30 minutes after the test WOD, to ensure that perceived exertion referred to the whole workout rather than the most recent exercise intensity.

Training load during the intervention

The training load for the participants was estimated using two methods. On the one hand, the first method only used the total time taken by the participants to complete the workouts. The average time for each WOD and the total time of the intervention were calculated. On the other hand, the second method used the total number of repetitions performed by each participant multiplied by the load used in the barbell weight during the workout. Like the time, the average load for each WOD and the total load for the entire CF training were calculated (Haff & Ph, 2010).

Statistical Analysis

The variables of TT performance in the four AMRAPs and total repetitions, VO_2peak, VO_2mean, HRpeak, HRmean, [La], CMJ, and RPE were analyzed using a factorial ANOVA with two levels (pre, post) and two factors (SL, RL), except for the three time points of 1RM in BS, CJ, and C (pre-, mid-, and post-). Additionally, absolute and relative changes in [La] and CMJ before and after TT were calculated to compare pre-post variations. Before ANOVA comparisons, data was analyzed for independence, homoscedasticity, and normality using Durbin–Watson, Levene, and Shapiro–Wilk tests. Means and standard deviations (M ± SD) of all data are presented. We determined the effect size (ES) in the within-subjects comparison using omega squared (ω^2), which has been suggested to correct the amount of variance explained based on the sample (LeCroy & Krysik, 2007). A post-hoc comparison was performed with the interaction between the time point and each variable with Tukey's correction and Cohen's d effect size interpretation (small: $0.01 \leq \omega^2 < 0.06$, medium: $0.06 \leq \omega^2 < 0.14$, and large: $\omega^2 \geq 0.14$). Moreover, for a deeper analysis of the change in performance variables, including 1RM, CMJ, and repetitions in the TT, we performed an individual athlete analysis using the Smallest Worthwhile Change (SWC) as an attempt to provide a more realistic assessment of performance adaptations for the SL and RL groups (Hopkins et al., 2009). A constant of 0.2 was used to establish the SWC threshold in trained populations or athletes (Turner et al., 2015). The sample was divided into responders and non-responders based on SWC, and the responder rate was expressed as a percentage per group. Lastly, differences between total and mean time training between groups and total and mean load were compared using an independent t-test. Similar analyses were conducted for each WOD at different time points in SL and RL. Statistical significance was set at $p < 0.05$. All statistical tests and graphics were executed by JASP (v0.18.3.0).

RESULTS

The primary finding of this study is that only the RL group had a significant improvement in their total performance in the TT after the CF intervention, as shown by a significant interaction effect (ES = 0.54, p = 0.009). In contrast, the SL group showed a non-significant trend toward improvement (ES = 0.44, p = 0.085). Moreover, both groups improved their performance in the four AMRAPs of the TT from pre- to post-intervention (ES = 0.51, p = 0.001), but with no significant interaction.

Regarding strength adaptations, the RL group significantly increased their 1RM in the BS (ES = 0.31, p = 0.005) and the C (ES = 0.16, p = 0.027). Meanwhile, no significant changes were observed in the SL after CF training (Figures 3A and 3B). In both groups, no significant changes in CJ performance were observed.

Regarding neuromuscular adaptations, neither group significantly improved CMJ height at the end of the intervention. In addition, the TT produced a significant decrease in CMJ height immediately after the TT in these two groups, both before (SL: ES = 0.83, p < 0.001; RL: ES = 0.7, p < 0.001) and after the intervention (SL: ES = 0.57, p < 0.001; RL: ES = 0.55, p < 0.001). Nevertheless, no significant interaction effects were observed between groups or across time points (Table 2).

Table 2. Participants´ changes as mean±SD in the standardized and relativized groups in the abovementioned study variables measured in the Tibana Test.

	SL (n=10)			RL (n=12)				
	Pre (M±SD)	Post (M±SD)	p-val	Pre (M±SD)	Post (M±SD)	p-val	p-val time effect	p-val group x time effect
AM1 (reps)	60.1±8.9	62.6±5.2	0.511	56±8	59.3±7.5	0.203	0.025	0.733
AM2 (reps)	70±10.2	74.1±11.7	0.282	66.8±7.2	69.8±10.5	0.491	0.030	0.698
AM3 (reps)	81.1±18.4	85.7±15.9	0.601	81.3±15.4	90.1±11.9	0.073	0.014	0.413
AM4 (reps)	79.7±16.1	84.8±19.3	0.184	74.3±9.8	79.3±15.4	0.141	0.006	0.976
WOD (reps)	290.9±41.1	307.2±44.9	0.063	278.4±27.3	298.4±35.4*	0.009	0.001	0.657
VO_2peak (#)	41.1±5.5	40.2±5.8	0.804	41.9±3.8	40.2±2.9	0.251	0.064	0.536
VO_2mean (#)	29±2.6	28.8±3.9	0.995	29.6±2.4	29.2±3.3	0.948	0.595	0.852
HR_{peak} (bpm)	174±5.4	172.9±5.2	0.695	176.5±6.1	174.3±6.6	0.137	0.028	0.444
HR_{mean} (bpm)	157.1±6.5	155.7±5.5	0.783	157.7±4.8	154.9±6.1	0.227	0.026	0.498
Δ[La] (mmol/l)	12.2±1.6	13.8±1.8	0.084	12.7±2.7	13.9±2	0.175	0.003	0.669
ΔCMJ (%/cm)	-17.2±6.2	-13.5±7.9	0.577	-14.2±10.6	-11.9±9.1	0.756	0.120	0.776
RPE (0/10 au)	8.2±0.4	8.6±0.7	0.406	7.7±0.7	7.9±0.7	0.701	0.001	0.233

Note. SL = Standardized Group; RL = Relativized Group; AM = As Many Repetitions as Possible; reps = repetitions; WOD: Workout of the Day; # = ml/min/kg; bpm = beats per minute; Δ[L] = percentual change in blood lactate; mmol = millimoles per litre; Δ% CMJ = percentual change in countermovement jump; au = arbitrary units; **p* < .05

Cardiopulmonary variables derived from CPET analysis (VO_2peak, VO_2mean, HRpeak, and HRmean) showed no significant changes pre- to post-intervention. Similarly, blood lactate levels did not show significant interaction effects between time points or between groups, as shown in Table 2.

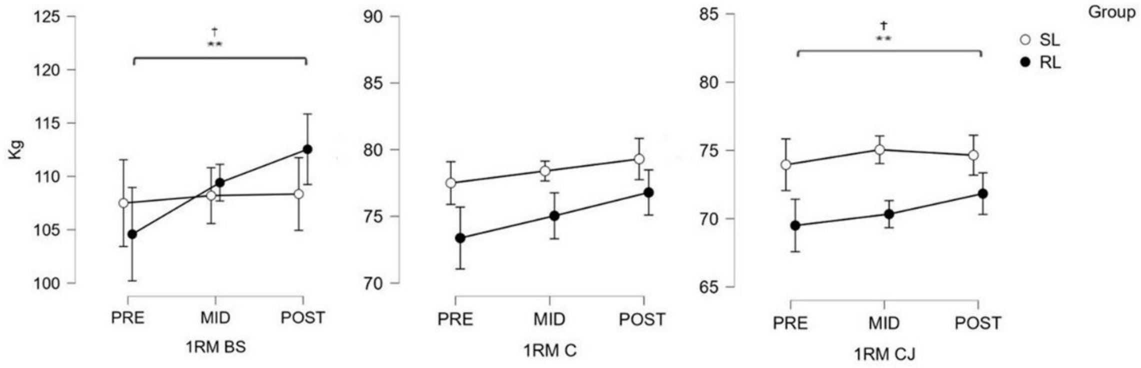

Figure 3. Representation of the three 1RM assessments in the back squat, the clean and jerk, and the clean during the intervention.

Note. A) 1RM in the Back Squat; B) 1RM in the Clean and Jerk; C) 1RM in the Clean. SL = Standardised Group represented with hole circles; RL = Relativised Group represented with solid circles; PRE = First week of the intervention; MID = Fifth week of the intervention; POST = Ninth week of the intervention (the last week).

**p < .01; † differences between PRE and POST in RL group

Perceived effort remained similar between groups pre- and post-intervention. However, in the first assessment, the RL group reported a lower RPE than the SL group, which had a significantly higher final RPE at the end of the TT (ES = 0.59, p < 0.001).

Training load analysis revealed no significant differences in total training time or total load between the RL and SL groups during the intervention. However, analyzing each Hero WOD, the SL group spent significantly more time in the first Zembiec WOD (ES = 0.55, p = 0.004) and the first and second Grettel (ES = 0.49, p = 0.017; ES = 0.51, p = 0.01), Puccio (ES = 0.52, p = 0.008; ES = 0.54, p = 0.005), and DT workouts (ES = 0.68, p < 0.001; ES = 0.61, p < 0.001). Besides, the SL group lifted a significantly greater total load in the first and second Klepto (ES = 0.51, p = 0.011; ES = 0.49, p < 0.017), Puccio (ES = 0.51, p = 0.01; ES = 0.48, p < 0.018) and DT WODs (ES = 0.37, p < 0.001; ES = 0.42, p < 0.001) compared to the RL group (Figure 4).

Finally, we found that 70% of the SL participants were responders, while over 83% of the individuals in the RL group had a positive result and were classified as responders to the training intervention. However, this difference was not statistically significant. Moreover, regarding 1RM improvements, fewer than 20% of SL participants showed clear individual progress in the BS and C, while approximately 50% of RL participants improved in both exercises. A similar trend was observed in CMJ height, where around 20% of SL participants were classified as responders, compared to over 45% in the RL group (Figure 5).

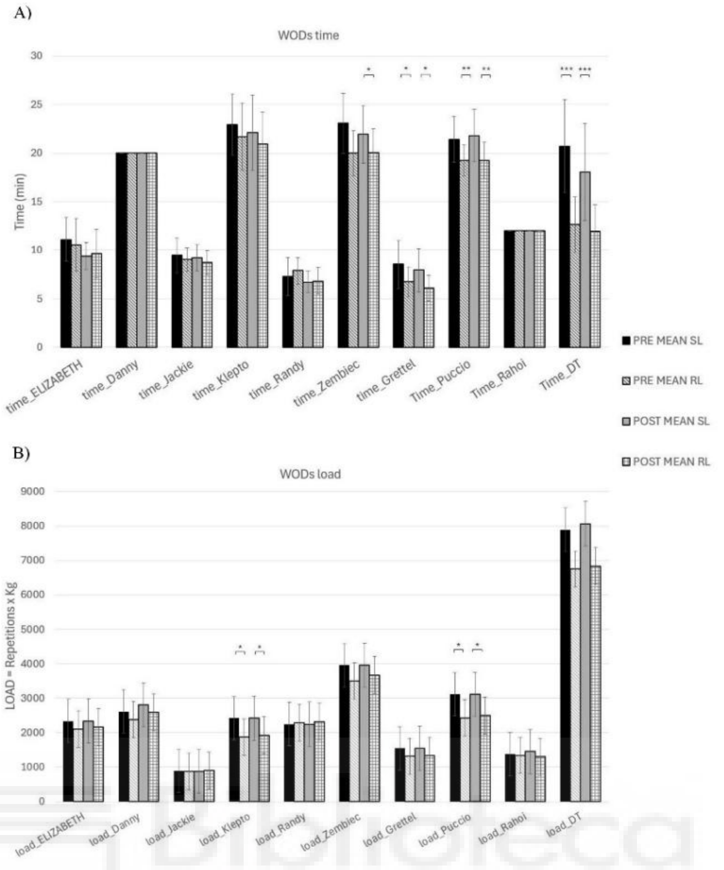

Figure 4. Training load during the intervention in SL and RL groups of athletes. A) Average training time; B) Average training load (repetitions x Kg in the barbell). The bars represent whether it was the first or second WOD and the intervention group (SL or RL).

Note: *<.05; **<.01; ***<.001

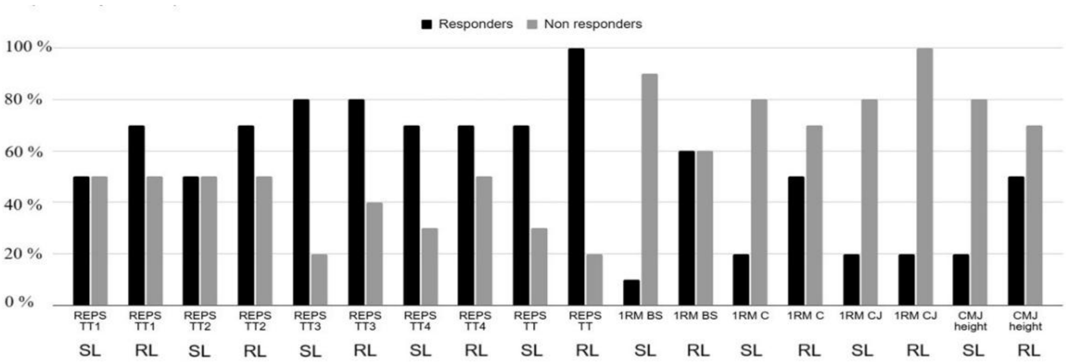

Figure 5. Individual stats of responders, non-responders and negative responders in 1RM performance, CMJ height and Tibana Test performance by group (SL or RL) using Smallest Worthwhile Change (SWC).

DISCUSSION

This study aimed to investigate the effects of a CF intervention on experienced participants by comparing workout performance, strength gains, jump height, and physiological adaptations between a group training with individualized loads and a group training with prescribed Rx loads in WODs. Our hypotheses regarding a major increase in performance during TT in the RL group could not be confirmed, because although the RL was the only group that improved significantly, the interaction between group and time did not show differences. The second hypothesis was confirmed concerning the increase in 1RM in the BS and C in the RL participants, however, no differences were found in the improvement in CMJ height after the intervention in either group. The third hypothesis was not supported, as no significant differences in VO_2, HR, and [La] were found within and between groups before and after the TT was performed, despite both groups showing high acute effects on neuromuscular and physiological responses before and after this test.

The CF intervention improved TT muscular endurance in both groups, but only the RL group showed statistically significant improvements. This suggests that using a load relative to %1RM may be more effective than fixed Rx loads for enhancing CF performance. The scientific literature lacks comparable studies on individualizing barbell loads in CF, but benefits from intensity adjustment based on HR and Heart Rate Variability (HRV) have been reported. DeBlauw (2021) found significant improvements in a 10-minute AMRAP using HRV-based programming (+12.21% repetitions) versus pre-established protocols (+14.7% repetitions), with better fatigue management in the HRV group. Similarly, polarised CF training produced comparable improvements to "all out" high-intensity training over six weeks in experienced athletes (10.7% and 9.9% seconds improvement in WOD Jackie) ´ (Held et al., 2024b). In particular, lower training loads in HR and HRV-based groups produced similar performance improvements, suggesting that efficient load management enhances adaptation.

Regarding strength gains, the RL group improved 1RM in BS and C, while no changes were observed in the SL group. These findings align with Posnakidis (Posnakidis et al., 2022) who reported greater 1RM gains with high loads (>80% 1RM) versus moderate loads (~60% 1RM) after eight weeks of high-intensity functional training (HIFT) (+19.2% vs. +10.4% kg in the bench press). Our RL participants trained with an average load of 60% 1RM, while the SL group used fixed loads at varying %1RM, making it difficult to establish a consistent training stimulus. Another study with experienced CF athletes showed significant improvements in the squat (+4.7%) and the deadlift 1RM (+4.5%) after eight weeks of CF training even though the load was only individualized in the strength portion of the session, not the WOD itself (Banaszek et al., 2019). This suggests that load individualization during the WOD may further enhance strength adaptations.

CMJ height did not improve significantly in either group. This contrasts with previous HIFT studies showing increases between 6.2% and 8% in CMJ after 6 to 8 weeks (Posnakidis et al., 2022; Romero-Arenas et al., 2018). We hypothesized that RL would improve CMJ due to individualized adjustments in power-based barbell movements and the high frequency of triple extension exercises (e.g., box jumps, and burpee pull-ups). However, our participants' high training experience (≥12 months) may have reduced sensitivity to neuromuscular adaptations. Furthermore, CF often emphasizes efficiency over maximal jump height (e.g., box jumps are performed to minimize time rather than maximize height), which may explain the lack of improvement in CMJ despite including jumping exercises in the intervention WODs.

No significant differences were found in VO_2, HR, or [La] values before and after the intervention. This aligns with previous research showing that HIFT induces rapid muscle fatigue before VO_2peak is reached, limiting improvements in aerobic capacity. Rios (Rios et al., 2024) highlighted that VO_2 kinetics in HIFT involve a rapid component followed by a slower phase, which may explain the lack of change in VO_2 values. Held (Held et al., 2024b) reported similar results, and even measures on a stationary bike, no significant differences were found in VO2peak, neither in the group that alternated between moderate and high intensity nor in the group that always trained at high intensity, no found differences in VO_2peak after a six-week CF intervention despite performance improvements, suggesting increased efficiency rather than improved aerobic capacity. However, studies with untrained participants have reported VO_2max improvements of +6.4% to +10.4% following CF interventions (3,41).

The perceived effort after TT showed levels over seven (7.7–8.6 points)on the Borg CR10 scale, expressing the nature of the high intensity in CF training workouts (Oliver-Lopez et al., 2022). Interestingly, only the SL group reported a significant increase in perceived effort after the intervention (+10.5% AU), suggesting that RL participants managed fatigue better due to load individualization. Throughout the intervention, RL participants reported a mean RPE of 7.3 ± 0.91, while SL reported 7.7 ± 0.85. Despite the high perceived effort, CF athletes often report a sense of enjoyment and adherence due to the social dynamics within the CF box (Heinrich et al., 2014).

The SL group spent 10.6% more time training than the RL group, but no significant differences were found in total load or total training time across WODs. However, significant differences were observed in several WODs, where SL participants spent more time training and lifted more weight. Similar results were found when training was individualized by HR zones, where lower training loads produced similar performance gains (Held et al., 2024b). In parallel, the two studies had the same coincidence in the group that individualized the WODs intensity, either by HR or barbell weight, there were no injuries. In contrast, injuries were found in the groups that did not relativize this variable, and some participants did not complete the intervention. Nonetheless, CF combining strength training, gymnastics, and endurance shows heterogeneity in exercise prescription and reduces the understanding of which factors should be considered when prescribing WODs (e.g., exercise volume, intensity, and duration) and which method CF coaches should use to prescribe and quantify the load of their athletes to achieve the desired adaptations and manage fatigue (Sharp et al., 2024).

Moreover, the individual analysis of SWC to see if the athletes improved in the study variables showed a higher level of responders in the RL group (50%–60% of positive responders) than participants of the SL. All these ideas are developed to transfer them to CF training, as sports scientists recommend individualizing training parameters, such as intensity to optimize results in their athletes, seeking an optimal dose of stimuli to maximize beneficial effects in search of future adaptations (Coakley & Passfield, 2018). Gianzina's review (Gianzina & Kassotaki, 2019), argues that elite athletes should adhere to individualized training methods with clearly defined objectives and periodicity in training with rest periods. In the same line Oliver-López (Oliver-Lopez et al., 2022) warns that since the literature reports mostly positive, but some negative responses and adaptations, this training must be prescribed by qualified trainers who appropriately adjust training variables to avoid future negative effects.

This study has some limitations. Firstly, the relatively short duration of the intervention may limit the observation of chronic adaptations that typically emerge from a longer-term periodization. While this is a relevant limitation, it aligns with the broader trend observed in CF research, where intervention studies often employ short durations. This is particularly evident when the training interventions involve CF-experienced athletes who often perform their own CF programming, with the issue of interrupting their established training routines. Secondly, there was no control group to determine if these adaptations were the main protagonists of the intervention. However, including a control group in this type of intervention presents some challenges. CF participants would need to leave their habitual training, which is often impractical. Alternatively, including participants engaged in other types of strength training for this control group would introduce variability, as they lack the specific familiarity and conditioning associated with CF. Thirdly, and like a future recommendation, the possibility to improve the individualization of training by monitoring HR zones for a holistic approach to the adjustments of the CF training load. Furthermore, in the same way, the challenge of individualizing or establishing biomechanical rules to prescribe the gymnastic movements for each CF participant. All these possible issues aim to adapt the training load to participants in an efficient way and follow a dose-response model.

Practical applications

The authors recommend prescribing depending on their percentage for every athlete and not in function of Rx or scale established loads. The process of choosing a percentage for every WOD is detailed in the next three steps. 1) Determine reference loads: consider the average load of Rx athletes that scientific literature reports for BS, CJ, and C movements (see Supplementary Sheet 1) and calculate the percentage of 1RM that represents the WOD. 2) Estimate Unknown 1RMs: apply the correlations and regressions in the literature to estimate 1RMs for other movements (e.g., thruster or front squat) with the three main exercises mentioned above. 3) Adjust for multiple barbell movements in the same WOD: base the load on the overhead movement to ensure appropriate intensity in the workout.

CONCLUSIONS

This research addresses the question of individualizing barbell weights in strength movements from the data available in the literature, i.e., the athletes' 1RM and the weights set for the Hero WODs. We aimed to provide the optimal load for each participant to maximize the benefits of this training, and we can now state that the use of individualized loads resulted in improvements in performance and maximal strength, besides the fact that all athletes completed the intervention, unlike the athletes who followed the fixed Rx loads.

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Conflicts of interest

The authors declare no conflicts of interest.

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Dicen que expresar gratitud a lo largo de la vida hace que las personas sean capaces de experimentar mayores momentos de bienestar y felicidad. Tras la finalización de esta tesis, no podría concluir dicho texto sin expresar la infinita gratitud a todas las personas que de forma directa o indirecta han colaborado en esta etapa y han hecho que sea posible.

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“*La amistad duplica las alegrías y divide las angustias por la mitad*” – Francis Bacon