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

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

1 Center of Research, Education Innovation and Intervention in Sport, Porto Biomechanics Laboratory, Faculty of Sport, University of Porto, 4200-450 Porto, Portugal; up201200394@edu.fade.up.pt (R.C.); jpvb@fade.up.pt (J.P.V.-B.); ricfer@fade.up.pt (R.J.F.)
2 Porto Biomechanics Laboratory, Faculty of Sport, University of Porto, 4200-450 Porto, Portugal
3 Department of Sport Sciences, Exercise and Health, University of Trás-os-Montes e Alto Douro, 5001-801 Vila Real, Portugal; victormachadoreis@gmail.com
4 Research Center in Sports Sciences, Health Sciences and Human Development, 5001-801 Vila Real, Portugal
5 Research Center in Physical Activity, Health and Leisure, Faculty of Sport, University of Porto, 4200-450 Porto, Portugal; danielmgon@fade.up.pt
6 Laboratory for Integrative and Translational Research in Population Health, 4050-091 Porto, Portugal
* Correspondence: manoel.rios@hotmail.com or up201600074@up.pt

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

Keywords: biomechanics; CrossFit®; snatch; technique analysis

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1. Introduction

Physical fitness benefits related to high-intensity exertion and a sense of community have led CrossFit® to an unprecedented level of global popularity [1]. In fact, the CrossFit® program has quickly become one of the fastest-growing training concepts, boasting over 15,000 affiliated training centers and 5 million athletes worldwide [2]. CrossFit® workouts involve functional movements executed at high intensity, known as the workout of the day, typically including gymnastics exercises, metabolic conditioning, and Olympic weightlifting [2,3]. These activities are executed in rapid succession, often prioritizing maximal numbers of repetitions within a specific period or completing a designated set of repetitions in the shortest time duration [4,5]. Like other high-intensity resistive exercise modes, CrossFit® improves body composition, muscle strength and cardiorespiratory fitness [1]. To assess these changes in fitness levels and monitor work capacity, CrossFit® uses benchmark workouts, like Cindy [6,7] and Fran [8,9] that are among the most extensively studied [2]. The benchmark workouts are standardized, meaning athletes use the prescribed weight or height, complete the specified number of repetitions, and follow the

exact movement patterns, to ensure performance comparability with athletes worldwide, regardless of location or environment [2,9,10]. However, mounting evidence indicates that certain CrossFit® workouts, paired with insufficient recovery periods, may heighten the risk of overload, fatigue and injury, especially in poorly trained individuals [1,5].

The incidence of injuries in CrossFit® spans strength-related sports from 0.2–18.9/1000 h of participation, mirroring rates observed in other sports like weightlifting and powerlifting [11,12]. In fact, the predetermined external loads and repetition volumes set for CrossFit® routines can exert a significant influence on the kinematics and kinetics of movements, with the imposition of significant loads on the knee, hip and shoulders amplifying the susceptibility to injuries [5,12]. Potential contributor to CrossFit-related injuries, particularly shoulder injuries, is muscular fatigue from the high number of repetitions performed during sessions [13]. For example, the CrossFit® Isabel workout requires completing 30 power snatch repetitions within a 2 min period (with a predominance of the anaerobic component), with a constant external load of 61 kg [4,10]. This emphasis on anaerobic exertion, coupled with fatigue accumulation throughout the routine (due to the accumulation of hydrogen ions reducing pH and causing metabolic acidosis, as well as the inhibition of phosphofructokinase) [14], may compromise movement biomechanics, increasing injury risk for crossfitters [1,5]. The relationship between fatigue and movements, especially prevalent in CrossFit® workouts that feature technically demanding weightlifting exercises and heavy loads, necessitates attention [5,12,15].

The power snatch, by lifting the bar from the floor to a position above the head with the upper limbs fully extended in one continuous movement [16,17], is a commonly incorporated exercise in strength and power training within CrossFit® programs [1,4]. It stands out as the most technical component of weightlifting in CrossFit® competitions, demanding a precise mechanical execution [16,17]. In weightlifting, success in the snatch is contingent upon the load lifted and is achieved through optimal force generation by maintaining specific positions during precise phases that align with an individual's optimal biomechanics [18]. Numerous kinetic and kinematic variables related to both the barbell have been documented to elucidate the snatch and its individual components, including power, velocity and barbell displacement [16,19]. Previous studies indicate that as the load increases, the pull duration rises, while the maximal and mean velocities, as well as the power output, decrease [19,20]. In addition, it has been reported that the snatch initial phase is slower and emphasizes force, while the second phase is faster and leans towards power [19,20].

Despite the increase in scientific studies due to the growing popularity of CrossFit®, there remains significant room for future research on the biomechanical analysis CrossFit® benchmark workouts (e.g., Isabel). In fact, while many studies have evaluated the biomechanics of the snatch [16,19,21], research on its use with high volume (e.g., 30 repetitions) and constant load (e.g., 61 kg) is limited. Really, the Isabel workout may alter snatch kinematics, potentially increasing joint load and injury susceptibility [5,12]. Hence, given the cumulative overload volume on crossfitters, it is crucial to characterize this workout along its full duration.

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

2. Materials and Methods

2.1. Participants

Eleven highly trained male crossfitters, aged 28.4 ± 6.0 years, with an average height of 176.8 ± 10.3 cm, body mass of 87.7 ± 11.8 kg, lean mass of 44.4 ± 7.5%, fat mass of 11.2 ± 4.2%, body mass index of 28.0 ± 2.4 kg/m^2 and 5.6 ± 1.6 years of CrossFit® training experience, volunteered for the current study. Participants were recruited through detailed announcements at local CrossFit® affiliate gyms based on the following criteria:

(i) training CrossFit® at least five times a week for a minimum of three years and having prior experience in national and international competitions; (ii) the ability to complete the Isabel workout in under 2 min; (iii) age between 20 and 30 years and clearance according to the Physical Activity Readiness Questionnaire; (iv) being free of injuries and known illnesses; and (v) not using performance-enhancing drugs. Male who did not meet the inclusion criteria were excluded, as were those with cardiovascular, pulmonary or neuromuscular conditions that could affect the results. Participants were instructed to maintain their usual nutritional habits, abstain from alcohol and caffeine consumption, and avoid intense physical activity 48 h before the test. Detailed information about the experimental procedures, associated risks and benefits of participation were provided. All volunteers read and signed an informed consent form in accordance with the Declaration of Helsinki and guidelines of the World Medical Association for research involving humans, with the study being approved by the local Ethics Committee (CEFADE212019).

2.2. Experimental Design

Following a cross-sectional design, each experienced crossfitter underwent an evaluation under consistent environmental conditions (20 °C ambient temperature, 60% humidity and between 8 a.m. to noon [12 p.m.]). All tests were conducted in the same laboratory facilities and supervised by experienced researcher. Each participant underwent a series of descriptive measurements to evaluate body composition and anthropometrics. Body mass and height were taken before the experimental session using a bioimpedance scale (InBody 120, Biospace, Seoul, Republic of Korea) and a stadiometer (model 220, SECA, Hamburg, Germany), and body mass index calculated by dividing body mass by height squared. Each crossfitter was assessed using the standard methods established by the International Society for the Advancement of Kinanthropometry [22]. After a 10 min warm-up period for joint mobility and Isabel specific exercise with low loads (10 repetitions at 40% of Isabel's training weight), each participant performed the Isabel workout at maximal exertion. An expert researcher supervised each repetition of the snatch to ensure proper execution of the movements. Kinematic and kinetic variables were measured continuously and performance timing was quantified using a Seiko stopwatch (Yokohama, Japan). The effort was analyzed globally and divided in its initial, middle and final phases corresponding to 10, 20 and 30 repetitions, respectively).

2.3. Isabel Workout

The Isabel is a CrossFit® benchmark workout consisting of completing 30 power snatches for time, using a prescribed weight of 61 kg for male and 43 kg for female. The objective is to perform the snatches as quickly as possible, maintaining proper form and technique throughout the workout [4,10]. The Isabel workout was chosen because it consists of only one exercise and requires a high number of repetitions performed as quickly as possible. In addition, the snatch is a very popular and commonly practiced exercise in CrossFit® routines. To qualify for participation in the present study, crossfitters had to complete the workout in 2 min or less, as this time frame classifies them as elite crossfitters [4].

2.4. Methodology

The participants kinematic data were recorded using eight Miqus video cameras (Qualisys AB, Göteborg, Sweden), operating at 100 Hz and 720 p resolution, with a maximum calibration error of 0.50 mm [23]. Full-body markerless kinematics with 6° of freedom were obtained by post-processing the video recordings using the Theia Markless (2023.1.0.3161_ P14, Kingston, ON, Canada) software. In addition, the bar displacement was obtained by placing a 12.0 mm retrorreflective marker in each extremity and recording its position using a 12 cameras infrared motion capture system (Miqus, Qualisys AB, Göteborg, Sweden), operating at 100 Hz and in synchrony with the markerless video cameras. The markerless and marker-based kinematics were merged in Visual3D (HAS-

Motion, Kingston, ON, Canada), where further processing and analysis of the data was performed [23]. The bar lift total time, maximal and average power and velocity were obtained from the start to the end of the lift movement. The movement initiation was considered as the first instant that the bar velocity crosses the 0.2 m/s threshold in the upward direction, while the end lifting was considered at the maximum height of the bar. The angles of the knee, hip and shoulder joints were recorded when the bar crossed these anatomical shoulder positions (Figure 1). All angles were calculated as the angle of the distal segment in relation to the proximal segment. All kinematic data was filtered with a 6 Hz bidirectional low-pass Butterworth filter in Visual3D software (v2024.03.3).

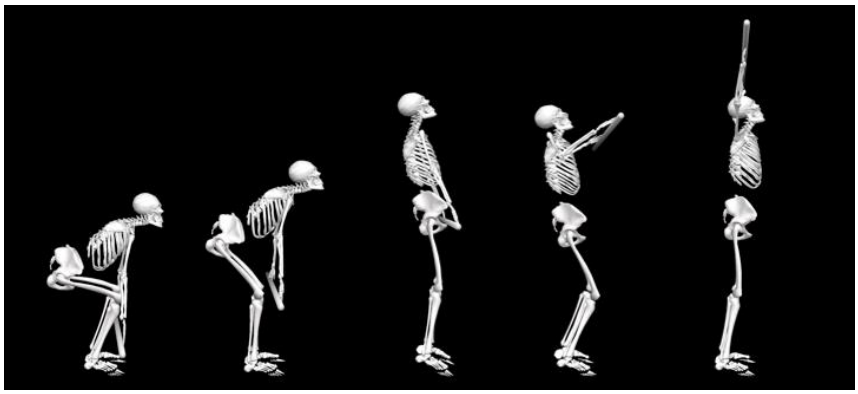


Figure 1. Individual kinematic example of the sagittal plane at the initial phase, bar crossing the knee, hip and shoulder, and final position (from left to right, respectively).

2.5. Statistical Analysis

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

3. Results

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

when the bar crosses the knee (initial vs. middle, $p = 0.006$, $d = 0.2$; initial vs. final, $p = 0.019$, $d = 0.6$). In contrast, an increase in knee extension was observed as the bar crosses the shoulder (initial vs. middle, $p = 0.039$, $d = 0.4$; initial vs. final, $p = 0.039$, $d = 0.8$).

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

Variables	Initial Phase	Middle Phase	Final Phase	Overall
Lift total time (s)	1.51 ± 0.18	1.71 ± 0.27 *	1.97 ± 0.20 * #	1.77 ± 0.25
Maximal lift velocity (m/s)	2.64 ± 0.12	2.48 ± 0.15 *	2.32 ± 0.13 * #	2.48 ± 0.12
Average lift velocity (m/s)	1.19 ± 0.14	1.08 ± 0.14 *	0.98 ± 0.11 * #	1.08 ± 0.12
Maximal lift power (W)	1425.24 ± 262.47	1350.33 ± 275.95 *	1259.99 ± 248.85 * #	1338.81 ± 255.60
Maximal lift power (W/kg)	15.58 ± 2.34	14.75 ± 2.59 *	13.80 ± 2.49 * #	15.26 ± 2.58
Average lift power (W)	636.80 ± 149.30	566.75 ± 159.99 *	493.30 ± 134.57 *	567.26 ± 141.32
Average lift power (W/kg)	6.94 ± 1.41	6.15 ± 1.56 *	5.41 ± 1.53 *	5.73 ± 1.42
Time to knee cross (% lift total time)	18.10 ± 2.10	11.70 ± 6.90	10.90 ± 6.80	15.60 ± 2.00
Time to hip cross (% lift total time)	34.20 ± 4.00	29.30 ± 4.50 *	27.50 ± 5.10 *	30.00 ± 3.00
Time to shoulder cross (% lift total time)	39.70 ± 16.80	35.50 ± 15.80 *	30.90 ± 13.90 *	39.00 ± 8.70
Time to maximal lift velocity (% lift total time)	39.20 ± 4.10	33.20 ± 5.30 *	29.40 ± 4.00 *	33.80 ± 3.70
Knee angle at knee cross (°)	37.49 ± 14.54	34.44 ± 9.44	29.04 ± 3.49	33.66 ± 8.90
Knee angle at hip cross (°)	40.66 ± 18.80	41.65 ± 16.02	36.79 ± 9.77	19.25 ± 11.07
Knee angle at shoulder cross (°)	35.18 ± 9.40	39.34 ± 9.30 *	42.86 ± 9.23 *	36.41 ± 13.51
Hip angle at knee cross (°)	62.62 ± 24.80	58.33 ± 23.36 *	53.60 ± 19.99 *	58.18 ± 22.63
Hip angle at hip cross (°)	20.29 ± 11.63	18.38 ± 10.82	19.07 ± 5.98	39.70 ± 14.33
Hip angle at shoulder cross (°)	9.21 ± 6.94	9.45 ± 7.43	9.80 ± 6.33	9.49 ± 6.74
Shoulder angle at knee cross (°)	42.26 ± 4.45	41.02 ± 4.15	40.35 ± 3.10	41.21 ± 3.75
Shoulder angle at hip cross (°)	48.56 ± 5.28	48.15 ± 5.29	47.12 ± 5.98	47.94 ± 5.20
Shoulder angle at shoulder cross (°)	68.74 ± 11.37	69.68 ± 10.22	69.33 ± 10.42	69.25 ± 10.56

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

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

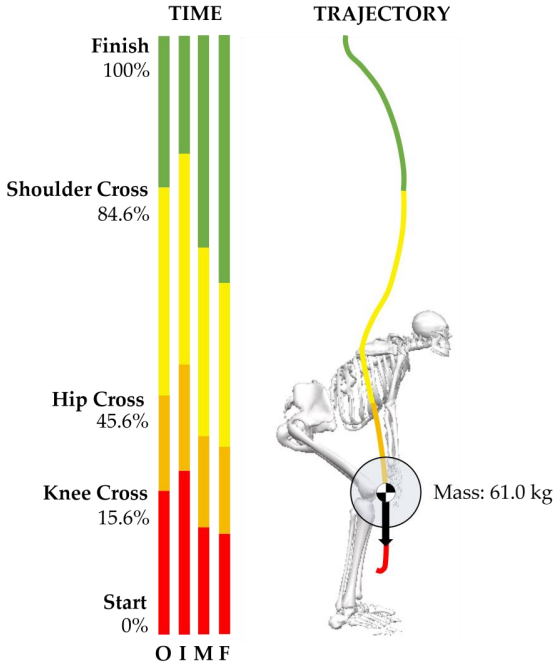


Figure 2. Representation of the lift trajectory and time until it the bar crosses the knee (red), hip (orange), shoulder (yellow) and achieves the finish position (green). The chromatic range depicts the distribution of these phases during the overall exercise (O), initial phase (I), middle phase (M)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

4. Discussion

We assessed the biomechanics characteristics of the Isabel CrossFit® workout, which is typically performed in ~120 s and elicits very significant energy demands [4]. Our mains findings were that: (i) an increase in total lift time, and decrease maximal lift velocity and maximal lift power occurred in the middle phase and continued to decrease throughout the elevation; (ii) average lift power decreased until the workout final phase, remaining constant in the last two phases; (iii) there was a gradual decrease in the time from lift until the bar crossed the hip and shoulder throughout the routine, with the lowest values being observed in the final phase; and (iv) as the number of repetitions succeed, a trend toward a decreased hip flexion was observed during the last two phases when the bar crossed the knee, while an increase in knee extension was noted when the bar cross the shoulder. Collectively, these outcomes indicate that the high demands of Isabel workout impact the power profile of crossfitters, while also affecting changes in hip flexion throughout the specific workout without compromising the other joints.

While the biomechanics of the snatch during single repetition efforts are well documented in the literature, particularly in weightlifting and powerlifting [16,19], research in the context of CrossFit® is scarce, especially using benchmark workouts under real exercise conditions. In the current study, the substantial volume of repetitions with a constant load impacted the total lift time, velocity and maximal power production throughout the workout. This decline was expected and aligns with the increased metabolic demands and muscle fatigue associated with extreme-intensity exercise over time [4,10]. Moreover, the decrease in the average lift power until the workout final phase, while remaining constant in the last two phases, suggests a potential adaptation of performance despite the continued effort. This adjustment in pacing likely reflects an attempt to maintain consistent performance levels despite increasing fatigue, slowing the velocity of muscle contraction [24,25].

The time from lift until the bar crosses over the knee, hip and shoulder progressively increased throughout the Isabel routine, correlating with the increase in time to reach maximal lift velocity. These results are supported by findings that elite weightlifters experience a decline in barbell velocity, potentially due to excessively rapid initial movement or fatigue [19,26]. Previous research has demonstrated that the Isabel workout performed in ~2 min exhibits a greater anaerobic predominance, reflecting the increased recruitment of type II muscle fibers, which are more susceptible to fatigue [4]. Furthermore, increases in external load during multi-joint exercises can result in greater task demands on skeletal muscle function [25,27]. Even if we did not observed a rise in external load (e.g., 70–90% of one repetition maximum), there was an increase in the total volume of repetitions, influencing the time instant the bar crosses the joints [28].

The observed decrease in hip flexion during the last two phases of the Isabel workout, as the bar crosses the knee, aligns with studies on biomechanics of weightlifting [19]. When the crossfitter takes the bar off the floor, the knee angle tends to increase towards maximum extension [16,26] and the lifter actively pushes the knees towards the bar, facilitating the transition into the pull point [19,21]. This pattern often relates with a decrease in hip flexion as the numbers of repetitions increase, reflecting the dynamic adjustments in movement mechanics throughout the workout [29]. This suggests that during the period between lifting and crossing the bar at the hip, the lower limbs may be participating less in generating force, increasing the demand on the trunk extensor muscles to complete the required numbers of repetitions [29]. In fact, no angular differences were observed when the bar cross the shoulder point, indicating that the inertia of the bar has already been overcome [19]. This further suggests that the primary cause of angular changes can be attributed to a potential lower limbs fatigue, resulting in a reduction of the lift velocity and the associated power decrease observed in the last two phases of the routine.

In the absence of a dedicated study on power snatch performed with fixed load and numbers of repetitions completed within <2 min, the current study serves as a valuable point of reference, providing a degree of reliability to substantiate the present study obser-

vations and inferences. A number of limitations in our study warrant acknowledgment, particularly regarding the relatively small number of participants. It is important to note that despite the recruitment of experienced crossfitters, the fixed load of 61 kg for the Isabel workout, combined with the requirement to complete 30 power snatches ~2 min, presented a significant challenge. Despite these challenges, we believe the findings offer valuable insights, though we agree that increasing the sample size in future studies would enhance the generalizability and robustness of the results. Therefore, caution should be exercised when extrapolating the results of the current study to other cohorts or individuals with varying training experiences, as only healthy, experienced and male participants were recruited for this study. In future cross-sectional studies, comparing power snatch responses between novice and experienced crossfitters would provide valuable insights. Further studies should include electromyography assessment and other joint angles for an in-depth characterization of Isabel workout.

5. Conclusions

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

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Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Ethics Committee of the Faculty of Sport of the University of Porto (CEFADE212019) and the guidelines of the World Medical Association for research on humans.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: All data is contained within the article.

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Conflicts of Interest: The authors declare no conflict of interest.

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