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Exploratory Analysis of Physiological and Biomechanical Determinants of CrossFit Benchmark Workout Performance: The Role of Sex and Training Experience

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Abstract

CrossFit performance is influenced by physiological, neuromuscular, and perceptual factors, yet the extent to which these determinants vary by sex or training experience in standardized CrossFit Workouts of the Day (WODs) remains unclear. This study examined whether variables such as lactate accumulation, oxygen uptake dynamics, jump performance loss, and ventilatory responses relate differently to performance when stratified by sex and expertise. Fifteen trained athletes (eight males, seven females; overall mean age 27.7 ± 4.6 years) took part. Assessments included body composition, squat (SJ) and countermovement jumps (CMJ), and maximal oxygen consumption [VO_2max]. On a separate day, they performed Fran (21-15-9 thrusters and pull-ups, Rx or scaled) The prescribed ('Rx') version used standardized barbell loads (43 kg for men, 29 kg for women), while the scaled version involved reduced loads or pull-up modifications. Respiratory gas exchange and heart rate were continuously monitored, while blood lactate and jump performance were measured pre- and post-WOD. Workout completion time [s] was the primary outcome. Correlation heatmaps explored associations in the overall sample and by sex and expertise. Mean completion time was 422.1 ± 173.2 s (range: 200–840). Faster performance correlated with higher ventilatory responses [ΔVe, r = −0.60, p = 0.018], greater mean VO_2 (r = −0.62, p = 0.014), superior jump power [CMJ pre, r = −0.65, p = 0.009], and higher post-WOD lactate [r = −0.54, p = 0.036]. Sex-stratified analyses showed that males relied on ventilatory efficiency and neuromuscular power, whereas females were more constrained by performance loss and higher resting perceived exertion (RPE). Experts depended on ventilatory and neuromuscular efficiency, while initiates showed stronger associations with decrements in jump performance and higher RPE. These findings highlight subgroup-specific performance profiles and reinforce the need for tailored training strategies in CrossFit athletes.

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1. Introduction

CrossFit is a form of high-intensity functional training that combines gymnastics, Olympic weightlifting, and metabolic conditioning into varied, time- or task-based workouts known as "Workouts of the Day" (WODs) [1,2]. The multimodal integration of strength, aerobic, and technical demands creates unique challenges for performance prediction, since athletes must simultaneously sustain muscular power, aerobic efficiency, and skill execution under fatigue [3–5]. In recent years, there has been increasing interest in using physiological markers such as blood lactate concentration, maximal oxygen uptake (VO_2max, an indicator of aerobic capacity), heart rate (HR), and heart rate variability (HRV, a measure of autonomic regulation) alongside biomechanical indicators such as countermovement jump (CMJ) height and peak power to monitor training adaptations and fatigue responses in CrossFit athletes [6,7]. Recent research has increasingly examined both physiological and biomechanical variables in standardized CrossFit WODs. Acute studies have shown that benchmark workouts such as Fran and Cindy elicit substantial cardiovascular and metabolic stress, with heart rate exceeding 90% of maximum, lactate levels above 10 mmol·L^{-1}, and ratings of perceived exertion (RPE) greater than 8 [8]. Notably, Cindy produced higher oxygen uptake, relative maximal oxygen consumption (VO_2max), and energy expenditure compared with Fran. Beyond acute responses, predictors of performance have also been investigated. Leitão et al. [9] demonstrated that neuromuscular parameters, including maximal thruster and pull-up strength and 2 km rowing performance, were stronger determinants of Fran performance than physiological markers such as lactate or heart rate. These findings are consistent with systematic reviews reporting that CrossFit workouts induce acute alterations in hormonal, metabolic, and inflammatory markers (e.g., testosterone, cortisol, glycemia, cytokines, creatine kinase) [10]. At the same time, longitudinal interventions indicate chronic adaptations such as increased testosterone, reduced cortisol, and altered CD8 lymphocyte levels [11]. Importantly, sex-based differences have also emerged. Rios et al. [12] demonstrated that, although both men and women experienced substantial increases in oxygen uptake, heart rate, blood lactate, and glucose during Fran, men completed the workout faster and achieved higher peak VO_2 and HR values. Together, this evidence highlights that CrossFit performance is influenced by a complex interaction of physiological and biomechanical determinants, and that sex differences should be carefully considered when interpreting these responses.

Although physiological and biomechanical metrics provide valuable insight into training load and recovery [10,13–19], many studies have not accounted for individual-level moderators such as biological sex or training experience [20]. Sex-based differences in body composition [21,22], oxygen kinetics [19,23], hormonal responses [11,24,25], and ventilatory thresholds [26–29] are known to influence performance, with recent evidence showing that men generally complete benchmark workouts faster and exhibit higher peak cardiorespiratory responses than women [12,30–33]. Training experience also affects biomechanical efficiency [34–36], pacing strategies [37,38], and metabolic efficiency [39,40], all of which may moderate fatigue and performance outcomes [19,41]. Failing to consider these moderators risks biased or incomplete interpretations of performance data [14,19,42], thereby limiting the external validity of monitoring strategies across athlete subgroups [18,43,44], especially in the context of CrossFit. To date, only a limited number of studies have compared athletes' performance based on training experience in CrossFit [45–47]. Although research incorporating sex- and experience-based analyses remains scarce, recent work has begun to explore pacing strategies [37–39] and sex-specific physiological responses [12,30–33]. Nonetheless, these moderators are still often overlooked and may act as confounding factors [48,49] and lead to biased or misleading interpretations of performance outcomes [50]. Given the multifactorial and individualized nature of athletic performance [28,29], both sex and training experience may act as important sources of variability in the associations between physiological or biomechanical markers and WOD performance. Accounting for these moderators helps determine whether observed relationships are robust across subgroups or potentially biased [48–50].

In light of the aforementioned, the purpose of this study was to explore whether associations between physiological and biomechanical responses and performance differ when stratified by sex and training expertise. Specifically, we examined whether variables such as lactate accumulation, oxygen uptake dynamics, jump performance loss, and ventilatory responses were differentially associated with WOD completion time when stratified by sex or experience level. Given the exploratory nature of this study and the small sample size, we anticipated that sex might show stronger subgroup-specific differences in cardiovascular and ventilatory markers, whereas training expertise might play a smaller but still relevant role, particularly in relation to aerobic efficiency.

2. Materials and Methods

2.1. Procedures

Fifteen trained CrossFit practitioners volunteered to participate in this study, comprising eight males (27.9 ± 5.8 years; 75.2 ± 5.0 kg; 176.5 ± 5.7 cm) and seven females (27.4 ± 3.1 years; 61.0 ± 4.5 kg; 165.0 ± 3.4 cm). All participants were actively engaged in CrossFit training at the time of data collection, with at least one year of continuous practice and a minimum training frequency of three sessions per week. For descriptive purposes, participants were further classified according to training experience. Athletes with ≥4 years of consistent CrossFit practice were considered experts, following criteria established in previous research [43], resulting in seven experts and eight initiates. This categorization was not intended for formal between-group comparisons but served to illustrate the range of training backgrounds represented in the sample. All participants were informed of the study procedures and provided written informed consent. The study protocol was approved by the institutional ethics committee (process number: CE-UBI-Pj-2024-090-ID2772) and conformed to the principles of the Declaration of Helsinki.

Participants were required to meet the following inclusion criteria: (i) a minimum of one year of CrossFit training experience, (ii) participation in structured CrossFit training at least three times per week, and (iii) absence of musculoskeletal injuries in the six months prior to testing. Athletes were eligible if they were able to perform the benchmark Fran workout in either its prescribed (‘Rx’) or scaled form, according to their training capacity. Exclusion criteria included: (i) any known cardiovascular, respiratory, or metabolic disease, (ii) recent use of performance-enhancing substances, and (iii) inability to complete Fran under standardized conditions, regardless of version (Rx or scaled).

The final sample size (n = 15) was determined by the feasibility of recruiting trained athletes who met the inclusion criteria and were willing to undergo repeated physiological and biomechanical assessments in standardized CrossFit testing. This number is consistent with previous exploratory studies in CrossFit performance [8,9,12,30], which have reported samples ranging from 10 to 20 participants. Given the exploratory and hypothesis-generating aim of the present work, subgroup analyses (sex and training experience) were conducted with caution, acknowledging the limited statistical power and higher risk of Type II errors.

2.1.1. Baseline Anthropometry and Resting Heart Rate

Baseline anthropometric and physiological measurements were obtained at the start of the testing session. Stature (cm) was measured with a portable stadiometer (Seca GmbH & Co. KG, Hamburg, Germany), and body mass (kg), fat mass (%), lean mass (kg), and muscle mass (kg) were assessed using a digital bioelectrical impedance scale (Tanita MC-780, Tokyo, Japan). Bioelectrical impedance provides practical and non-invasive estimations of body composition, although its accuracy can be affected by factors such as hydration status. Nonetheless, it has been widely applied in sport science contexts, including studies with CrossFit athletes [51]. All measurements were performed barefoot and in light clothing, following manufacturer guidelines. Resting heart rate (HR, bpm) was recorded using a chest strap monitor (Polar S610, Kempele, Finland) after five minutes of quiet seated rest in a controlled environment to ensure physiological stabilization. HRV was recorded continuously during the workout using a chest strap monitor (Polar S610, Kempele, Finland), synchronized with the respiratory gas exchange system to ensure temporal alignment of physiological signals. Resting HRV was also assessed at baseline following five minutes of seated rest in a controlled environment, a method previously validated for reliability in applied sport science settings [6,7,52]. Furthermore, the use of HRV as a non-invasive marker of training load and recovery has been supported in prior high-intensity functional training studies [5].

2.1.2. Squat Jump (SJ) and Countermovement Jump (CMJ)

Neuromuscular performance was evaluated using a portable force platform (42 × 59 cm, Chronojump Boscosystem, Barcelona, Spain) with specific software (Chronojump v2.5.2-63 2025 Sept, Boscosystem, Barcelona, Spain). Before testing, participants completed a standardized warm-up consisting of 5 min of light cycling or jogging followed by dynamic mobility drills (hip, knee, and ankle) and two submaximal practice jumps for familiarization [4]. This instrument validity was previously reported in the literature [53,54].

For the squat jump (SJ), participants began from a stationary semi-squat position with knees flexed to ~90°, maintaining hands on the hips throughout (Figure 1, left picture). From this static position, they performed a maximal vertical jump without countermovement, extending the legs explosively in a single action. For the countermovement jump (CMJ, Figure 1 right picture), participants started from an upright standing position with hands fixed on the hips, executed a rapid downward countermovement, and immediately performed a maximal vertical jump. In both protocols, arm swing was eliminated by keeping the hands on the hips, and landing was standardized on the toes to ensure consistency [55]. Jump height (cm) was calculated from flight time using Chronojump's integrated software (sampling frequency: 1000 Hz). Each participant performed three attempts of both SJ and CMJ, interspersed with 50–60 s of passive recovery. The best performance was defined as the attempt with the highest jump height, and both jump height (cm) and peak power (W·kg^{-1}) from this trial were retained for analysis, as suggested in the literature [21,56]. Both tests were performed before and immediately after the WOD to quantify fatigue-induced changes in neuromuscular function.

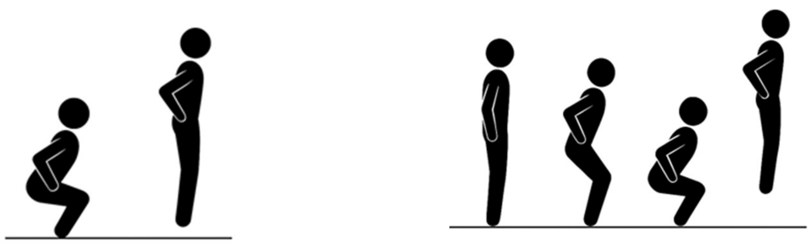

Figure 1. Standardized execution of squat jump (**left**) and countermovement jump (**right**) tests.

2.1.3. Workout of the Day (WOD), Respiratory Gas Exchange and Heart Rate Evaluation

The benchmark CrossFit workout Fran was selected as the performance test due to its established use in high-intensity functional training (HIFT) research and its ability to integrate strength and metabolic conditioning in a simple yet demanding format [19]. Fran consists of descending sets of 21, 15, and 9 repetitions of thrusters and kipping pull-ups, performed for time [57]. The prescribed (Rx) version uses a barbell load of 43 kg for males and 29 kg for females [23]. Participants unable to perform the workout as prescribed completed a scaled version with adjusted loads or pull-up modifications (e.g., band-assisted or jumping pull-ups) to ensure inclusivity while maintaining relative intensity [23]. Emphasis was placed on standardized execution (e.g., full squat depth and elbow lockout in thrusters) to guarantee safety and reliability of the performance outcome [58]. WOD completion time (s) were recorded as the primary measure of functional performance.

In addition to its popularity as a benchmark, Fran is characterized as a short-duration, high-intensity workout (typically completed within 3–7 min) that elicits substantial metabolic and cardiorespiratory stress, including elevated lactate, glucose, heart rate, and oxygen uptake [13,23]. These responses make it a suitable model for assessing both metabolic and mechanical determinants of performance in CrossFit athletes.

A schematic overview of the experimental protocol is presented in Figure 2, highlighting the sequence of assessments performed pre-WOD (anthropometrics, body composition, blood lactate, squat and countermovement jumps, resting HR), during the WOD (respiratory gas exchange, heart rate), and post-WOD (RPE, blood lactate, neuromuscular assessments, HR).

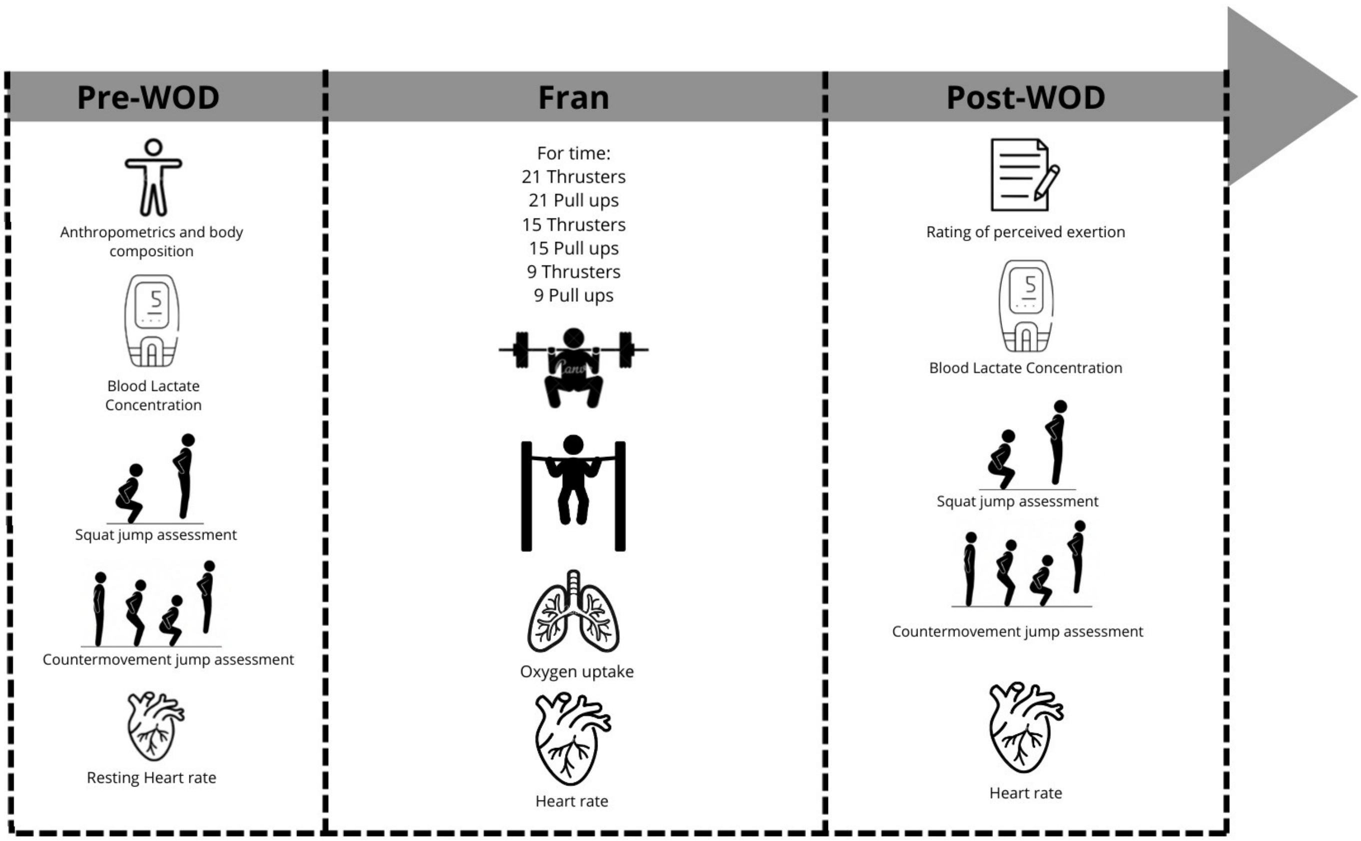

Figure 2. Schematic representation of the experimental protocol. Assessments were conducted pre-WOD (anthropometrics, body composition, blood lactate concentration, squat and countermovement jump performance, resting heart rate), during the benchmark CrossFit workout Fran (respiratory gas exchange, heart rate), and post-WOD (rating of perceived exertion, blood lactate concentration, squat and countermovement jump performance, heart rate).

Before the workout, participants completed a standardized warm-up designed to ensure adequate readiness for high-intensity exercise while minimizing the risk of premature fatigue. The warm-up consisted of 5 min of light-to-moderate intensity cycling on a stationary ergometer (≈50–60% of HRmax), followed by dynamic mobility drills targeting the shoulders, hips, and ankles. Participants then performed progressive sets of thrusters and pull-ups (2 sets of 10 repetitions with light loads and assistance, followed by 1 set of 5 repetitions at workout-specific load or scaled variation).

Following the warm-up, all participants observed a fixed 3 min passive rest interval before beginning the WOD. During this period, athletes remained seated or standing quietly while the respiratory gas exchange mask and heart rate monitor were checked and secured. This procedure standardized the transition across participants, ensuring comparable physiological readiness prior to exercise initiation [59,60].

During the WOD, respiratory gas exchange was measured breath-by-breath using a portable gas analyzer (VO_2 Master Health Sensors Inc., Vernon, Canada) with participants wearing a face mask throughout the workout. Heart rate (HR) was continuously monitored via a chest strap device (Polar S610, Kempele, Finland). The gas analyzer was calibrated for both volume and gas concentrations immediately before each session in accordance with manufacturer guidelines to ensure accurate and reliable data. Both the VO_2 Master system and the chest strap device have been validated in previous research [59,60], demonstrating strong agreement with laboratory-based systems and supporting their use in applied sport science settings.

All workout executions were continuously monitored by the same experienced researcher (certified CrossFit Level 1 Coach) to ensure adherence to standardized movement criteria (e.g., full squat depth in thrusters, elbow lockout during pull-ups). Any repetitions that failed to meet the prescribed standards were immediately corrected in real time, with athletes required to repeat the movement until valid. This procedure ensured consistency across participants and reliability of the recorded performance outcomes. No video recordings were used for post-analysis.

2.1.4. Blood Lactate

Capillary blood lactate concentration ($mmol \cdot L^{-1}$) was measured immediately before and after the WOD to evaluate metabolic response. For the pre-exercise measure, a sample (~5 μL) was collected from the earlobe following a period of seated rest to ensure a stable baseline [61]. The post-exercise sample was obtained within one minute of WOD completion to capture peak accumulation. All samples were analyzed using a portable lactate analyzer (Lactate Pro 2, Arkray Inc., Kyoto, Japan), which was calibrated before each testing session according to manufacturer guidelines [8]. The earlobe was disinfected before each puncture, and sterile, single-use lancets were employed to maintain hygienic standards [8,62]. All assessments were performed according to standardized protocols [8], with equipment calibrated before testing and procedures delivered by the same experienced assessors to ensure reliability and reproducibility [62].

2.2. Statistical Analysis

Data were first screened for normality using the Shapiro–Wilk test. Continuous variables are presented as mean ± standard deviation (SD), together with minimum and maximum values. Comparisons between sex (male vs. female) and training expertise (expert vs. initiate) were performed using the Mann–Whitney U test, given the small sample size and the non-normal distribution of some variables. Effect sizes for these comparisons were estimated using rank-biserial correlation coefficients to aid interpretation. Effect sizes (Cohen’s d) were calculated for group differences and interpreted as small (d < 0.50), medium (d = 0.50–0.79), or large (d ≥ 0.80) [24]. The associations between baseline physiological and neuromuscular predictors (e.g., VO_2max, HRV, CMJ, SJ) and the primary outcome (WOD completion time) were examined using Spearman's rank correlation coefficients. Exploratory subgroup analyses (sex and training experience) were conducted to examine whether associations varied across subgroups. Given the small sample size and the hypothesis-generating nature of this study, no corrections for multiple comparisons were applied. The results should therefore be interpreted with caution, acknowledging the increased risk of Type I error. Correlation strength was classified according to conventional thresholds: weak (ρ < 0.30), moderate (ρ = 0.30–0.49), and strong (ρ ≥ 0.50) [63].

Correlation matrices were generated for each analysis, and the results were visualized as heatmaps to facilitate the interpretation of association patterns across variables. In-workout and post-exercise responses (e.g., ΔHR, ΔVO_2, ΔVe, ΔCMJ, ΔSJ, lactate, RPE) were conceptualized as mediators and were not adjusted for in the primary analyses. To assess potential effect modification, exploratory subgroup analyses were conducted by sex and by expertise. The statistical significance was set at $p < 0.05$. All analyses were performed in JASP (version 0.95.0.0; University of Amsterdam, The Netherlands).

3. Results

3.1. Descriptive Statistics

Fifteen trained CrossFit athletes (8 males and 7 females) participated in this study. Male participants had a mean age of 27.9 ± 5.8 years, body mass of 75.2 ± 5.0 kg, and stature of 176.5 ± 5.7 cm, while female participants presented a mean age of 27.4 ± 3.1 years, body mass of 61.0 ± 4.5 kg, and stature of 165.0 ± 3.4 cm. Based on training background, 7 participants were classified as experts (≥4 years of consistent CrossFit practice) and 8 as initiates (<4 years).

Mean WOD completion time was 422.1 ± 173.2 s, with performance ranging from 200 to 840 s, highlighting substantial inter-individual variability (Table 1). Neuromuscular decrements were evident, with average reductions in squat jump (ΔSJ height: −2.77 ± 3.28 cm; ΔSJ power: −43.3 ± 52.8 W) and countermovement jump (ΔCMJ height: −4.09 ± 3.23 cm; ΔCMJ power: −69.2 ± 61.9 W). The physiological responses reflected high metabolic and cardiovascular stress, with large post-exercise increases in blood lactate (ΔLactate: +12.3 ± 1.6 $mmol{\cdot}L^{-1}$), oxygen uptake (ΔVO_2: +26.9 ± 5.5 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$), heart rate (ΔHR: +69.8 ± 16.1 bpm), and ventilation (ΔVe: +91.9 ± 21.6 $L{\cdot}min^{-1}$). Minimum HRV during the WOD showed a marked decline (ΔHRV: +40.3 ± 19.5 ms).

Table 1. Descriptive analysis for total sample WOD performance time and variations (Δ) of physiological and neuromuscular responses.

	WOD Time (s)	ΔSJ (cm)	ΔSJ (W)	ΔLactate [mmol/L]	ΔVO_2 [mL/kg/min]	ΔHR (bpm)	ΔVe [L/min]	ΔHRV	ΔCMJ (W)	ΔCMJ (cm)
Mean	422.1	−2.769	−43.28	12.26	26.88	69.80	91.92	40.27	−69.22	−4.093
SD	173.2	3.278	52.83	1.563	5.501	16.07	21.59	19.51	61.85	3.232
Min	200.0	−9.920	−165.6	8.900	16.70	45.00	57.50	8.000	−206.1	−9.545
Max	840.0	2.879	35.90	14.39	38.30	90.00	129.1	66.00	20.80	1.643

3.2. Comparisons Between Sex and Experience

Males exhibited significantly greater lean mass (65.7 ± 5.0 kg) compared to females (49.6 ± 4.5 kg; $p = 0.0016$, d = 2.20, large effect). Similarly, muscle mass was substantially higher in males (33.9 ± 3.0 kg) than in females (22.1 ± 2.0 kg; $p < 0.001$, d = 4.89, very large effect). No significant sex differences were observed for fatigue-induced reductions in countermovement jump height (ΔCMJ: −4.0 ± 3.2 cm vs. −4.2 ± 2.9 cm; p = 0.92, d = 0.05, small effect) or squat jump height (ΔSJ: −3.1 ± 2.4 cm vs. −2.4 ± 2.8 cm; p = 0.72, d = −0.19, small effect). Both sexes demonstrated comparable lactate accumulation following the WOD (ΔLactate: males 12.3 ± 2.5 mmol·L^{-1}, females 12.3 ± 2.8 mmol·L^{-1}; p = 0.99, d = 0.00, trivial effect). The figure that highlights the means and differences between sex are presented in Figure 3.

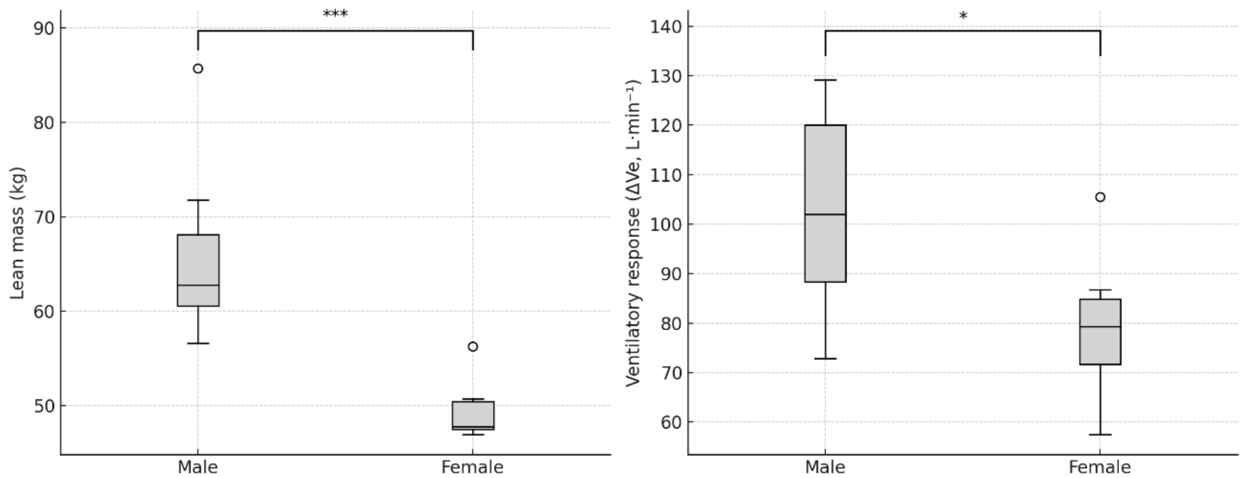

Figure 3. Boxplots (median, interquartile range, minimum–maximum, and outliers) of lean mass (kg) and ventilatory response (ΔVe, L·min^{-1}) stratified by sex. Asterisks indicate significant differences (* $p < 0.05$; *** $p < 0.001$).

Experts tended to have higher lean mass (61.4 ± 6.0 kg) compared to initiates (54.5 ± 7.2 kg), though this difference was not statistically significant (p = 0.23, d = 0.64, medium effect). Muscle mass did not differ meaningfully between groups (29.1 ± 4.8 kg vs. 27.6 ± 4.5 kg; p = 0.65, d = 0.23, small effect). Fatigue-induced reductions in jump performance showed moderate but non-significant differences, with experts experiencing greater CMJ decrements (−5.2 ± 3.3 cm vs. −2.9 ± 2.6 cm; p = 0.18, d = −0.75, medium effect). No clear difference was observed for SJ reductions (−3.1 ± 2.9 cm vs. −2.4 ± 2.5 cm; p = 0.72, d = −0.21, small effect). Post-exercise lactate accumulation was similar across expertise levels (12.8 ± 2.2 mmol·L^{-1} vs. 11.7 ± 2.8 mmol·L^{-1}; p = 0.22, d = 0.71, medium effect). Experts completed the workout significantly faster than initiates (309 ± 89 s vs. 514 ± 111 s; $p < 0.01$, d = 2.23, large effect). Pre-WOD CMJ power was higher in experts than in initiates (987 ± 208 W vs. 784 ± 116 W), though this difference did not reach statistical significance (p = 0.14, d = 0.93, large effect). The figure that highlights the means and differences between expertise are presented in Figure 4.

3.3. Associations with WOD Performance

In the overall sample, fewer variables showed significant correlations with WOD completion time (Figure 5). Faster performance was associated with greater lean mass (ρ = −0.46, $p < 0.05$ *) and larger ventilatory responses (ΔVe) (r = −0.65, $p < 0.01$ **). Other physiological (VO_2, lactate), neuromuscular (CMJ and SJ decrements), and perceptual (RPE) measures did not show significant associations with WOD performance in the overall analysis.

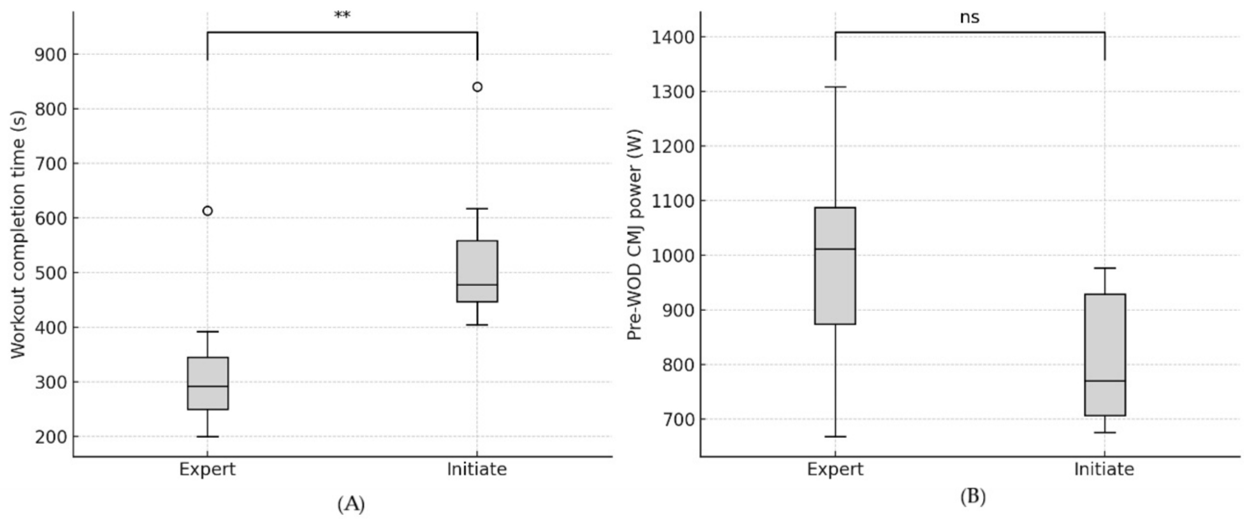

Figure 4. Boxplots (median, interquartile range, minimum–maximum, and outliers) of (**A**) workout completion time (s) and (**B**) pre-WOD countermovement jump (CMJ) power (W), stratified by expertise level. Asterisks indicate significant differences (** $p < 0.01$; ns = non-significant).

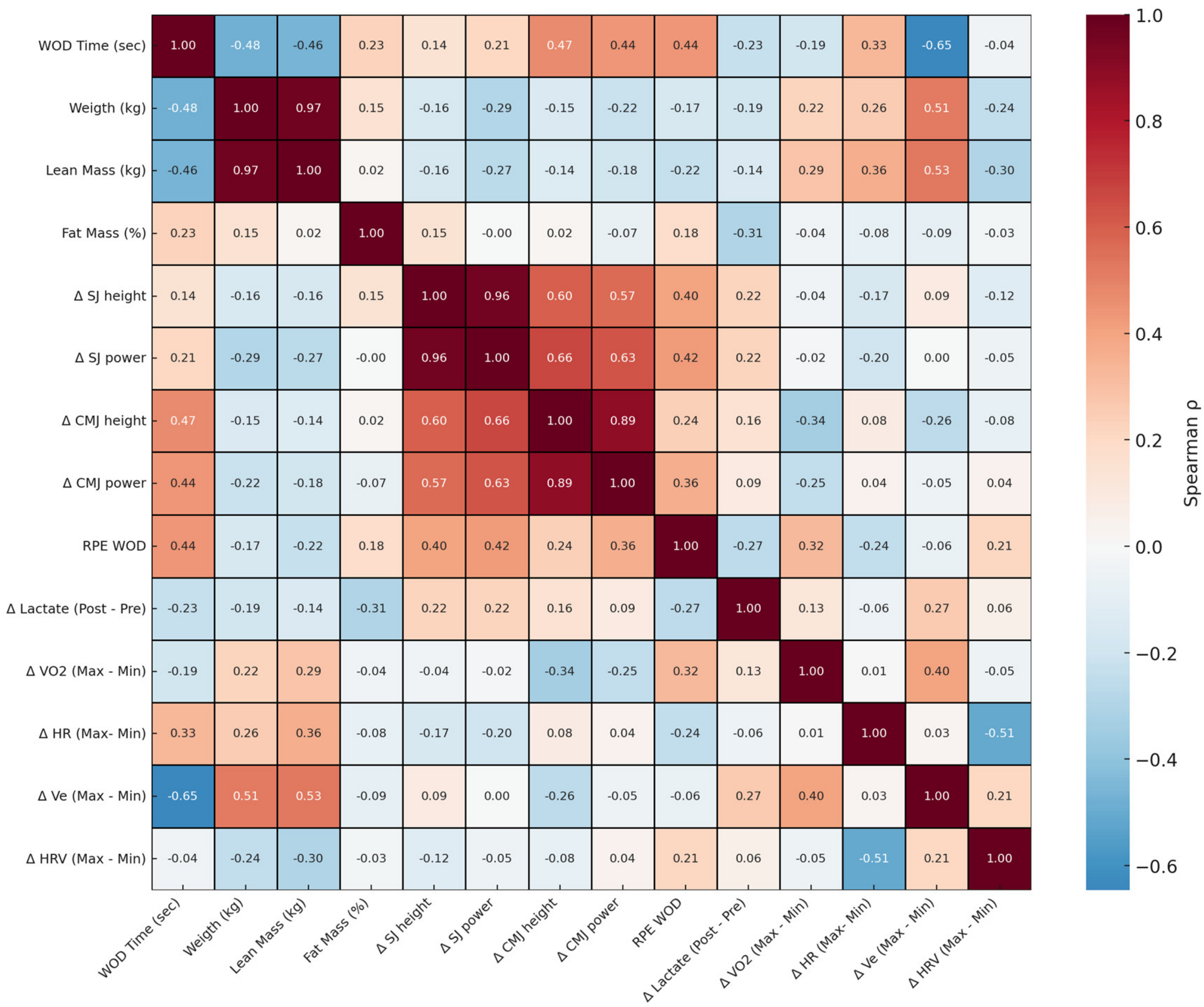

Figure 5. Spearman's rank correlation coefficients (ρ) between physiological, biomechanical, and perceptual variables and workout completion time (WOD Time, s) for the total sample ($n = 15$). Color scale indicates direction and magnitude of correlations (blue = negative, red = positive). Numeric values

represent correlation coefficients. Variables include body composition (weight, lean mass, fat mass), neuromuscular function (Δ squat jump [SJ] and countermovement jump [CMJ] height and power), perceptual responses (RPE), and physiological markers (Δ lactate, Δ VO_2, Δ HR, Δ Ve, Δ HRV).

Given the heterogeneity in physiological and neuromuscular determinants observed at the overall level, we next examined whether these associations differed by sex (Figure 6. Among males, WOD completion time was primarily explained by ventilatory efficiency, with a significant correlation for ΔVe (r = −0.76, $p < 0.05$ *). No other physiological, neuromuscular, or perceptual variables were significantly related to performance in this subgroup. By contrast, females exhibited a profile more closely tied to neuromuscular fatigue and RPE. Faster performance was associated with smaller decrements in CMJ power (r = 0.93, $p < 0.01$ **) and smaller decrements in CMJ height (r = 0.64, $p < 0.05$ *), while higher RPE values were linked to slower times (r = 0.81, $p < 0.05$ *).

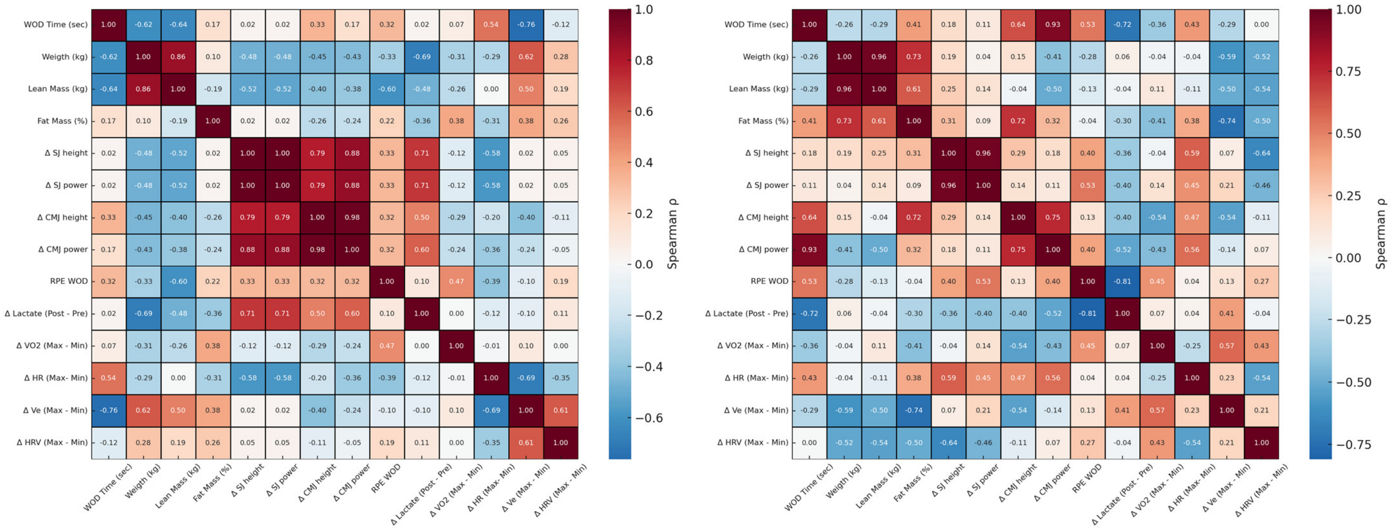

Figure 6. Spearman's rank correlation coefficients (ρ) between physiological, biomechanical, and perceptual variables and workout completion time (WOD Time, sec), stratified by sex (Male: $n = 8$, left panel; Female: $n = 7$, right panel). Color scale indicates direction and magnitude of correlations (blue = negative, red = positive). Numeric values represent correlation coefficients.

To further examine the impact of training background, we stratified the analyses by training experience (Figure 7). Among experts, faster WOD completion was associated with ventilatory efficiency and neuromuscular capacity, with significant correlations for ΔVe (r = −0.74, $p = 0.029$) and pre-WOD CMJ power (r = 0.74, $p = 0.029$). No other variables reached significance in this subgroup. In contrast, initiates displayed a performance profile more constrained by body composition, fatigue, and perception. Slower performance was significantly correlated with higher fat mass (r = 0.82, $p = 0.023$), greater decrements in CMJ height (r = 0.57, $p = 0.048$) and CMJ power (r = 0.93, $p = 0.002$), as well as higher RPE values (r = 0.59, $p = 0.046$).

Collectively, these analyses suggested that the WOD completion time is linked to multiple physiological, neuromuscular, and perceptual markers. However, the strength and nature of these associations varied across subgroups: ventilatory and neuromuscular capacities.

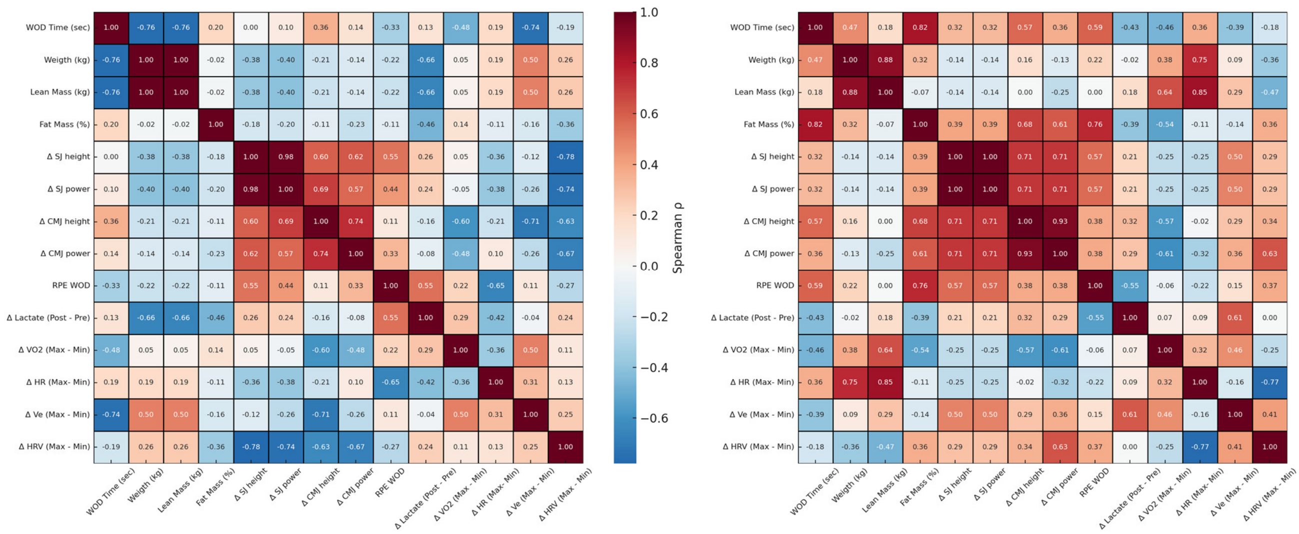

Figure 7. Spearman's rank correlation coefficients (ρ) between physiological, biomechanical, and perceptual variables and workout completion time (WOD Time, sec), stratified by training experience (Expert: n = 7, left panel; Initiate: n = 8, right panel). Color scale indicates direction and magnitude of correlations (blue = negative, red = positive). Numeric values represent correlation coefficients.

4. Discussion

This study aimed to investigate the physiological and biomechanical factors that influence performance in the CrossFit benchmark workout, Fran, and to explore whether sex and training experience moderate these associations. The defined hypothesis was partially verified because the influence of sex was clearly observed in both lean mass and ventilatory response, with males showing significantly higher values. In contrast, training expertise was associated with significantly faster WOD completion times, but no significant differences were observed in CMJ power values before WOD. This indicates that sex plays a stronger role in physiological determinants, especially ventilatory and body composition parameters, whereas training experience appears more relevant for performance-related outcomes, particularly workout pacing and completion time.

In the total sample, performance during Fran was primarily explained by body composition and ventilatory responses. Faster athletes displayed greater lean mass, which aligns with previous research identifying body composition as a determinant of CrossFit and CrossFit Open performance [5,22,64]. The importance of lean mass is likely related not only to the mechanical advantages it provides in strength-based tasks but also to its contribution to metabolic support during repeated high-intensity bouts [21]. Ventilatory responses (ΔVe) were also significantly associated with faster completion times, corroborating findings from [3,60], who reported that VO_2max and submaximal oxygen kinetics predict competitive CrossFit outcomes. These results emphasize the role of ventilatory dynamics, suggesting that athletes who can sustain large ventilatory responses perform more efficiently under the metabolic stress of Fran.

When examined by sex, distinct performance profiles emerged, reinforcing the biological basis of sex differences in exercise physiology. Males presented significantly higher lean mass and ventilatory responses (ΔVe) than females. In males, faster WOD completion was explained primarily by ventilatory efficiency, consistent with prior evidence that men exhibit higher absolute ventilatory capacity, which contributes to superior performance in high-intensity functional training [44,65]. In females, WOD performance was more strongly associated with neuromuscular fatigue markers and perceptual responses, including decrements in CMJ performance and higher RPE values. These sex-specific differences may be partially explained by underlying body composition. Greater lean mass in males enhances neuromuscular efficiency and supports the preservation of power output under fatigue [21,65]. In contrast, lower lean mass in females may increase the relative intensity of each repetition, amplifying fatigue-induced decrements in jump performance and elevating RPE [9]. This finding is consistent with prior evidence that female athletes often experience proportionally greater RPE during high-intensity multimodal exercise, despite sometimes showing higher resistance to peripheral fatigue in isolated tasks [60,66].

These sex-specific performance determinants are consistent with well-established physiological differences. Males typically exhibit greater absolute ventilatory capacity and oxygen kinetics, which enhance aerobic throughput during high-intensity exercise [19,23,44,65]. Consequently, ventilatory efficiency emerges as a stronger determinant of performance in men, enabling them to sustain greater aerobic flux during demanding multimodal tasks. In contrast, females generally present lower lean mass and absolute strength [21,22], which increase the relative intensity of each repetition and accentuate neuromuscular fatigue and perceptual strain during benchmark workouts [60,66]. These physiological characteristics explain why ventilatory dynamics were more predictive of WOD performance in males, whereas decrements in jump performance and RPE were more influential in females.

Stratification by training experience revealed further differentiation in the determinants of the WOD performance. In line with performance outcomes, experts also exhibited higher pre-WOD CMJ power on average compared with initiates (+20%). However, this difference did not reach statistical significance in our sample ($p = 0.132$). This trend suggests that neuromuscular performance may be superior in more experienced athletes, but larger samples are required to confirm this effect. These results are consistent with prior studies showing that advanced CrossFit practitioners develop higher aerobic capacity, refined pacing strategies, and superior neuromuscular outputs [14,67]. More experienced athletes also tend to present greater muscle mass and superior neuromuscular efficiency, which enhances their ability to sustain explosive power under fatigue [68]. On the other hand, novices were more constrained by body composition, fatigue, and perception. Slower performance was associated with higher fat mass, greater decrements in CMJ height and power, and higher RPE values. This is in line with evidence that initiators generally display higher fat mass and lower lean mass, which compromises the mechanical efficiency and increases the relative effort required to complete high-intensity tasks, thereby limiting performance [16,22,41]. Importantly, this reliance on perceptual and fatigue-related variables may reflect a lack of optimized pacing and technical efficiency, which typically improve with continued training exposure [43].

Taken together, these findings suggest that the determinants of CrossFit performance are subgroup-specific. The results of the present study suggested that males and experts benefit primarily from ventilatory and neuromuscular efficiency, females and initiates appear more constrained by neuromuscular fatigue, body composition, and perceptual load. This reinforces the need for tailored training approaches [69], focusing on fatigue management [70], body composition optimization [71], and pacing strategies in beginners and female athletes [8,72], while emphasizing ventilatory conditioning [73] and neuromuscular power in advanced and male athletes [12]. Upon that, it is possible to argue that the novelty and strengths of this research arose from being the first study to examine performance in a standardized CrossFit benchmark workout while jointly considering sex, training experience, and the combined contribution of metabolic, ventilatory, and biomechanical variables.

The present findings carry several implications for training prescription and athlete monitoring in CrossFit and other high-intensity functional training settings: (i) Performance in benchmark WODs such as Fran is underpinned by a multifactorial profile, with contributions from ventilatory capacity, neuromuscular power, and fatigue resistance. Consequently, coaches should adopt an integrative approach that develops both aerobic efficiency and explosive strength, rather than prioritizing a single fitness domain [14,42,64]. (ii) Subgroup analyses highlight the need for individualized training strategies. For male and expert athletes, interventions that optimize ventilatory efficiency and sustain neuromuscular power under fatigue may yield the greatest performance gains. This could be achieved through structured aerobic conditioning, power-based resistance training, and specific pacing practice during mixed-modal sessions [67,74]. Conversely, female and novice athletes may benefit more from strategies targeting fatigue tolerance, body composition improvements, perceptual regulation, and technical efficiency. These could include progressive exposure to benchmark WODs, perceptual load management (e.g., RPE-based training), and refinement of movement economy through skill-focused sessions [16,72]. (iii) The associations between performance, perceptual responses, and neuromuscular decrements emphasize the relevance of incorporating internal load monitoring into practice. Simple, non-invasive measures such as RPE tracking and jump performance assessments may provide valuable insights into fatigue status and readiness, supporting safer and more effective programming [43,75].

5. Limitations

Several limitations should be acknowledged when interpreting these findings. First, the relatively small sample size ($n = 15$), combined with subgroup analyses, limited statistical power and generalizability, and increased the risk of both Type I and Type II errors. Consequently, the results should be regarded as exploratory and hypothesis-generating rather than confirmatory. Second, although the use of heatmaps facilitated a broad exploratory assessment of associations, the absence of multivariate modeling prevents firm conclusions about the combined influence of variables. Larger cohorts are needed to validate these findings and support more robust analytical approaches. Third, performance was assessed using a single benchmark WOD, Fran. While Fran provides strong ecological validity [23], it represents a short-duration, mixed-modal workout that emphasizes ventilatory and fatigue-related demands. Incorporating WODs with different time domains and movement patterns would yield a more comprehensive perspective on CrossFit performance [43]. Fourth, contextual factors such as nutrition, sleep, and recovery status were not directly controlled, which may have influenced both physiological responses and performance outcomes [72,76]. While this reflects real-world training conditions, it also introduces variability that should be more rigorously controlled or monitored in future research. Fifth, the cross-sectional design precludes causal inference, underscoring the need for longitudinal or intervention-based studies. Finally, while portable measurement systems (e.g., gas analyzers and force platforms) enhanced ecological validity, they may exhibit small differences in precision compared to laboratory-grade instruments. Nonetheless, all devices employed have been previously validated and widely applied in field research [10,64,77], supporting confidence in the present findings.

Altogether, future research should aim to replicate these findings in larger and more diverse populations, incorporate multiple WOD formats, and integrate longitudinal monitoring to capture adaptation over time. Such approaches would provide a clearer understanding of how ventilatory, neuromuscular, and perceptual determinants interact to influence performance across the continuum of CrossFit experience.

6. Conclusions

This exploratory study suggests that, within the evaluated sample, performance in the CrossFit benchmark workout Fran may be influenced by an interplay of body composition, ventilatory efficiency, neuromuscular function, and perceived exertion. Importantly, the potential predictors of performance appeared to vary according to sex and training experience. Male and expert athletes tended to rely more heavily on ventilatory efficiency and neuromuscular capacity, whereas females and novice athletes seemed more constrained by decrements in jump performance, higher fat mass, and elevated RPE values. While these findings should be interpreted with caution given the small sample size, from a practical standpoint, the results also suggest potential directions for individualized training strategies: for example, male and expert athletes may benefit most from ventilatory conditioning and power-based resistance training, whereas female and novice athletes may respond better to programs emphasizing fatigue tolerance, technical efficiency, and perceptual load management. Such approaches may assist coaches in tailoring training plans while awaiting confirmation from larger-scale investigations.

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