

CrossFit Specific Performance in Recreational Athletes: The Importance of Strength and Fatigue Parameters

Alexandra Paula Ruão da Silva Pinto Malheiro

Tese para obtenção do Grau de Doutor em
Ciências do Desporto
(3^o ciclo de estudos)

Orientador: Prof. Doutor Mário António Cardoso Marques
Coorientador: Prof. Doutor Pedro Miguel Gomes Forte

Júri:
Prof. Doutor Daniel Almeida Marinho
Prof. Doutor Mário António Cardoso Marques
Prof. Doutor Victor Manuel Machado de Ribeiro dos Reis
Prof. Doutor João Paulo Gonçalves Moreira de Brito
Prof. Doutor Pedro Alexandre Duarte

Março de 2026

Declaração de Integridade

Eu, Alexandra Paula Ruão da Silva Pinto Malheiro, que abaixo assino, estudante com o número de inscrição D3348 de Ciências do Desporto da Faculdade de Ciências Sociais e Humanas, declaro ter desenvolvido o presente trabalho e elaborado o presente texto em total consonância com o **Código de Integridades da Universidade da Beira Interior**.

Mais concretamente afirmo não ter incorrido em qualquer das variedades de Fraude Académica, e que aqui declaro conhecer, que em particular atendi à exigida referência de frases, extratos, imagens e outras formas de trabalho intelectual, e assumindo assim na íntegra as responsabilidades da autoria.

Universidade da Beira Interior, Covilhã 16/03/2026

Dedication

In loving memory of Célia,

Whose light continues to dwell within every act of kindness and every trace of memory she left behind. Her laughter, smile, and quiet strength remain, unseen yet everlasting, woven in all that we are, and all that endures.

Acknowledgments

It was three years of perhaps the biggest challenge of my life so far. From self-discovery, growth, this process has made a massive impact on a personal and professional level. Reaching the end of this journey, I cannot fail to thank and acknowledge the importance of all those who contributed to the conclusion of this doctoral thesis, special thanks to:

Professor Mário Cardoso. Marques, for guidance, for making me realize that our own limits are unknown, that the process flows more naturally if you're willing to be humble, to trust and listen to the right people. For all the knowledge, supervision, counselling, patience, and opportunities to work with some amazing academics. The way you kept challenging and encouraging me made a significant contribution to who I am now. I owe you! Thank you for everything.

Professor Pedro Forte. None of this would've been possible without you. You saw some potential in me early on and never stopped believing that I would be able to complete this process. Thank you for all the shared knowledge, for being available at all hours, for all the sharing moments, for the constant encouragement, for helping me find myself, and for believing in me even when sometimes I couldn't do it. Thank you for always keeping me humble and for all the opportunities. There are no words to describe how grateful I am.

To Professor Diogo Luis Marques and Professor David Rodríguez-Rosell for all the guidance throughout the journey, for all the feedback, patience, and wisdom shared. It was a privilege to be able to work with you.

To the head coach, Ricardo Vieira, and all his CrossFit community for welcoming me to their box and participating in the experimental procedures. Thank you, NorthCall CrossFit!

To all my family, especially my parents and brothers. To my parents for all the values they transmitted, for all the efforts and support. To my brothers, my lifetime partners and supporters, thank you for all the encouragement, for always being there when needed. You are my pride. To my grandmother, for all the worries she shared with me, and for all the love and care she showed me, is the reason I believe in kindness above all. To my uncle, my pride and joy, for never stopping believing and encouraging me. My nieces for saving me more times than they'll ever know. Happiness is better when it's shared, and it's my privilege to do it with all of you.

To my friends, for always encouraging me and supporting the process! The lack of words seems unfair for all you've done.

To Rita Nogueira, for rationalizing my less positive thoughts, for always listening and never judging, for giving me the tools to tackle my intrusive thoughts, and for helping me rebuild my life. You are a sunray on my journey.

To my partner, for his love, friendship, and patience throughout this process. For being always there, understanding and encouraging me to be the very best version of myself.

I'm grateful to all of you!

List of Publications and Communications

The following studies support the present Ph.D. thesis:

Study 1 – Journal article

Malheiro, A., Forte, P., Marques, D. L., Rodríguez-Rosell, D., & Marques, M. C. (2025). Biomechanical and Physiological Demands of CrossFit: A Systematic Review. *Journal of Human Kinetics*. (in press)

Study 2 – Journal article

Malheiro, A., Forte, P., Marques, D. L., Rodríguez-Rosell, D., & Marques, M. C. (2025). Exploratory analysis of the correlations between physiological and biomechanical variables and performance in the CrossFit Fran benchmark workout. *Journal of Functional Morphology and Kinesiology*. **2025**, *10*(4), 387; <https://doi.org/10.3390/jfmk10040387>

Study 3 – Journal article

Malheiro, A., Forte, P., Marques, D. L., Rodríguez-Rosell, D., & Marques, M. C. (2025). Exploratory Analysis of Physiological and Biomechanical Determinants of CrossFit Benchmark Workout Performance: The Role of Sex and Training Experience. *Applied Sciences*. **2025**, *15*(19), 10796; <https://doi.org/10.3390/app151910796>

Additionally, the following communications were performed during the thesis:

Communication 1 – Poster Presentation

Malheiro, A., Forte, P & Marques, M. C. (2025). Relationship between maximal oxygen consumption in laboratory testing and CrossFit WOD. *CIDESD International Congress–Book of Abstracts (pp. 96)*. 5th of June to 7th of June 2025, Covilhã, Portugal.

Communication 2 – Poster Presentation

Malheiro, A., Forte, P & Marques, M. C. (2025). Lactate responses before and after a CrossFit WOD. *CIDESD International Congress– Book of Abstracts (pp. 98)*. 5th of June to 7th of June 2025, Covilhã, Portugal.

Communication 3 – Poster Presentation

Malheiro, A., Forte, P., Marques, D. L., Rodríguez-Rosell, D., & Marques, M. C. (2025). Sex differences in mechanical performance during resistance exercise at 80% of 1RM in CrossFit practitioners. *Jornadas de Biomecânica*. 25th of September to 26th of September 2025, Porto, Portugal.

Communication 4 – Abstract Submission

Malheiro, A., Forte, P., Marques, D. L., Rodríguez-Rosell, D., & Marques, M. C. (2025). Sex-specific biomechanical determinants of CrossFit performance. *Jornadas de Biomecânica – Book of Abstracts (pp. 66)*. 25th of September to 26th of September 2025, Porto, Portugal.

Resumo

Na última década, o CrossFit consolidou-se como uma prática de treino de força/condição física de alta intensidade e também como um desporto competitivo de crescente popularidade. Apesar da sua ampla difusão, persistem incertezas relativamente aos principais determinantes fisiológicos e biomecânicos do desempenho em Workouts of the Day (WODs), sobretudo quando consideradas diferenças individuais como o sexo e a experiência de treino. Assim, o objetivo geral desta tese consistiu em analisar de forma integrada as exigências fisiológicas e biomecânicas do CrossFit e identificar os preditores de desempenho em praticantes recreativos. Para tal, foram seguidos os seguintes passos: i) revisão sistemática da literatura sobre as exigências fisiológicas e biomecânicas do CrossFit; ii) uma análise experimental das associações entre variáveis fisiológicas, biomecânicas e o desempenho no WOD Fran; e iii) um estudo sobre o impacto do sexo e da experiência de treino nas relações entre respostas fisiológicas, biomecânicas e performance. Os resultados indicaram que o WOD induz respostas cardiovasculares, metabólicas e neuromusculares elevadas, mas com grande heterogeneidade metodológica entre estudos. Observou-se que as variáveis como a ventilação, o consumo médio de oxigénio (VO_2 médio), a frequência cardíaca e a potência neuromuscular explicam parte significativa do desempenho no WOD Fran. Além disso, tendências sugerem que a força máxima e a potência relativa poderão ser preditores mais relevantes em homens, enquanto a capacidade aeróbia e a força de membros superiores apresentaram maior influência nas mulheres. A experiência de treino parece contribuir para melhor performance, possivelmente através da maior eficiência técnica e menor fadiga. Em síntese, os resultados sugerem que a performance no CrossFit poderá ser explicada pela interação entre determinantes fisiológicos e biomecânicos, moduladas por características individuais, reforçando a importância de abordagens individualizadas na prescrição e monitorização do treino nesta modalidade.

Palavras-chave

CrossFit; treino de alta intensidade; fisiologia; biomecânica; performance; sexo; experiência de treino

Resumo Alargado

O presente capítulo integra e contextualiza o trabalho desenvolvido ao longo da tese de doutoramento intitulada “*CrossFit Specific Performance in Recreational Athletes: The Importance of Strength and Fatigue Parameters*”. Inicia-se com uma introdução geral, onde são apresentadas as questões centrais de investigação, bem como os objetivos gerais e específicos. Posteriormente, descrevem-se de forma sintética os estudos realizados, incluindo a revisão sistemática e os trabalhos experimentais. O capítulo conclui com a exposição das principais conclusões alcançadas e com a identificação de perspectivas para futuras investigações na área.

Introdução Geral

Durante as últimas décadas, o CrossFit tem-se afirmado como uma das práticas de exercício físico com maior crescimento a nível mundial, contando com milhares de ginásios afiliados e milhões de praticantes em todos os continentes (Mehrab et al., 2022; Rios et al., 2024). Na sua génese, o CrossFit é uma modalidade de treino de força/condição física de alta intensidade, caracterizada pela combinação de exercícios de levantamento olímpico, ginástica e condicionamento metabólico realizados em elevada intensidade e frequentemente sob condições de fadiga (Feito et al., 2018; Dominski et al., 2022; Malheiro et al., 2025). Esta estrutura multimodal, organizada em treinos denominados *Workout of the Day* (WODs), é utilizada tanto para fins de saúde e manutenção da aptidão física como para otimização da performance (Meier et al., 2022; Martínez-Gómez et al., 2019; Butcher et al., 2015). Paralelamente, o CrossFit consolidou-se também como um desporto competitivo, com expressão internacional através dos *CrossFit Games* e de circuitos competitivos locais e regionais, nos quais os atletas são avaliados pela sua capacidade de completar WODs padronizados no menor tempo possível ou com o maior volume de repetições (Mangine et al., 2020; Maté-Muñoz et al., 2017). Esta dupla natureza, simultaneamente modalidade de treino e desporto competitivo, contribui para a complexidade e relevância científica do CrossFit, tornando-o um modelo de estudo para investigar as respostas e adaptações fisiológicas e biomecânicas ao exercício de alta intensidade (Pyzybyliski & Franco, 2022; Stroobant et al., 2021).

Diversas revisões narrativas e sistemáticas têm evidenciado que o CrossFit induz melhorias específicas no desenvolvimento da força e tamanho muscular e capacidade

cardiorrespiratória (Claudino et al., 2018; Dominski et al., 2021; Meier et al., 2023). Contudo, permanece em aberto a questão sobre quais são os principais determinantes fisiológicos e biomecânicos do desempenho em WODs, já que estudos experimentais apontam para múltiplos fatores, desde variáveis neuromusculares (p. ex., uma repetição máxima [1RM], salto vertical, potência) até marcadores fisiológicos (p. ex., consumo máximo de oxigênio [$VO_{2máx}$], ventilação, lactato sanguíneo), sem consenso sobre o peso relativo de cada um (Butcher et al., 2015; Martínez-Gómez et al., 2019; Mangine et al., 2020; Zeitz et al., 2020).

Se olharmos para a literatura científica, a maioria dos estudos investigou separadamente dimensões fisiológicas ou biomecânicas, sem integrar de forma sistemática ambos os domínios para compreender o desempenho no CrossFit. Essa fragmentação metodológica limita a interpretação global das exigências impostas pelo treino e pela competição, originando resultados muitas vezes contraditórios. Assim, torna-se pertinente sintetizar a evidência existente para identificar os parâmetros mais estudados, as metodologias mais consistentes e as lacunas de conhecimento que justificam novas investigações (Estudo 1).

Outra limitação recorrente nos estudos publicados é a ausência de análises de fatores individuais, como o sexo ou a experiência de treino cumulativamente, que podem influenciar significativamente a resposta às exigências fisiológicas e biomecânicas do CrossFit. Diferenças biológicas entre homens e mulheres, nomeadamente na massa muscular, nos limiares ventilatórios e na resistência à fadiga, assim como o papel da experiência acumulada na eficiência técnica e na gestão de esforço, sugerem que o desempenho em WODs pode ser determinado por preditores distintos consoante o subgrupo analisado (Dexheimer et al., 2019; Schlegel & Křehký, 2022; Zeitz et al., 2020). Todavia, até ao momento, poucos trabalhos exploraram estas variáveis de forma comparativa ou preditiva, o que limita a aplicabilidade prática das recomendações para treinadores e atletas de CrossFit. Neste sentido, justifica-se a realização de estudos observacionais que identifiquem quais os preditores biomecânicos e fisiológicos que melhor se relacionam com o desempenho em WODs e de que modo estes variam em função do sexo e da experiência de treino (Estudo 2).

Destaca-se também que, mesmo quando se exploram variáveis como a capacidade ventilatória, o consumo de oxigênio, a acumulação de lactato ou a fadiga neuromuscular, raramente é analisado se o sexo e a experiência competitiva atuam como confundidores ou moderadores das relações entre estas respostas agudas ao WOD e o desempenho final

(Hunter et al., 2023; Malheiro et al., 2025). Essa lacuna metodológica pode levar a interpretações enviesadas, uma vez que associações observadas a nível global podem não se verificar em subgrupos específicos (Hunter et al., 2023; Malheiro et al., 2025). Assim, torna-se fundamental examinar até que ponto as características individuais influenciam a resposta aguda em variáveis biomecânicas (i.e., neuromusculares) e fisiológicas e a relação que essa resposta estabelece com o desempenho em WODs, clarificando as bases fisiológicas e biomecânicas que sustentam a variabilidade individual durante um WOD padronizado (Estudo 3).

Objetivos e Hipóteses

Tendo em conta os aspetos referidos, o propósito central desta tese foi contribuir para uma compreensão mais aprofundada dos fatores fisiológicos e biomecânicos que condicionam o desempenho no CrossFit. Para esse fim, foi delineada uma estratégia de investigação assente em duas vertentes complementares: por um lado, uma síntese crítica da evidência existente através de uma revisão sistemática; por outro, a realização de estudos transversais com carácter exploratório que permitam associar, no intuito de clarificar, em contexto aplicado, os principais preditores de desempenho biomecânico e fisiológico no CrossFit. Assim, o objetivo geral da tese consiste em analisar de forma integrada as exigências fisiológicas e biomecânicas do CrossFit e explorar as suas associações com o desempenho em praticantes recreativos, considerando o papel confundidor do sexo e da experiência de treino. Desta forma, os três estudos que compõe a presente tese, têm como objetivos:

- Estudo 1: realizar uma revisão sistemática da literatura para identificar os principais parâmetros fisiológicos e biomecânicos analisados no CrossFit e a sua relação com o desempenho específico de competição.
- Estudo 2: examinar os principais preditores fisiológicos e biomecânicos do desempenho num WOD padronizado, considerando diferenças associadas ao sexo e à experiência de treino.
- Estudo 3: analisar o papel do sexo e experiência de treino enquanto possíveis confundidores ou moderadores de relações entre variáveis fisiológicas e biomecânicas (p. ex., capacidade ventilatória, consumo de oxigénio, lactato, fadiga neuromuscular) e tempo de execução num WOD padronizado.

A realização desta sequência de estudos permitirá evoluir de uma síntese compreensiva do conhecimento existente para uma modelação preditiva e, finalmente, para uma explicação mecanicista, assegurando uma contribuição progressiva e coerente para a literatura. Em última análise, espera-se que esta tese contribua para clarificar os determinantes do desempenho no CrossFit e forneça orientações úteis para a prescrição, monitorização e individualização do treino em atletas desta modalidade.

Desta forma, e de acordo com a literatura previamente publicada, é possível compreender que o desempenho no CrossFit resulta de uma interação complexa entre componentes fisiológicas e biomecânicas. Estudos prévios sugerem que a força máxima, a potência e a eficiência neuromuscular se associam a melhores tempos de execução (Butcher et al., 2015; Mangine et al., 2020), enquanto variáveis fisiológicas, como o VO_2 máx, a ventilação e a capacidade de tamponamento metabólico, também parecem contribuir para o desempenho (Martínez-Gómez et al., 2019; Zeitz et al., 2020). No entanto, estas relações são influenciadas por características individuais, nomeadamente o sexo e a experiência de treino, que modulam tanto as respostas fisiológicas como a expressão biomecânica do esforço (Dexheimer et al., 2019; Schlegel & Křehký, 2022).

Assim, foi definida como hipótese geral da presente tese que o desempenho no CrossFit é determinado por um conjunto interdependente de fatores fisiológicos e biomecânicos, cuja influência relativa varia em função do sexo e da experiência de treino. No intuito de responder especificamente a esta hipótese geral, foram estabelecidas três hipóteses específicas, com as devidas justificações, correspondendo a cada um dos estudos que compõem a presente tese, a saber:

- Estudo 1: a hipótese de que o CrossFit induz respostas fisiológicas e biomecânicas elevadas foi estabelecida com base em estudos prévios que documentam aumentos significativos na frequência cardíaca, VO_2 máx e concentração de lactato, bem como reduções no desempenho neuromuscular após WODs de alta intensidade (Claudino et al., 2018; Kliszczewicz et al., 2017; Meier et al., 2023). Hipótese: os estudos publicados sugerem que os determinantes fisiológicos e biomecânicos do desempenho em WODs são múltiplos e interdependentes, mas permanecem inconsistentes devido à heterogeneidade metodológica existente.

- Estudo 2: a hipótese de que variáveis fisiológicas e biomecânicas se associam ao desempenho num WOD padronizado foi formulada com base em evidência que relaciona o $VO_{2máx}$, a ventilação e a potência muscular com o rendimento em tarefas de alta intensidade (Mangine et al., 2020; Schlegel & Křehký, 2022). Cria-se a hipótese de que, em praticantes recreativos de CrossFit, medidas fisiológicas (VO_2 médio, frequência cardíaca, ventilação) e biomecânicas (potência, salto vertical, força máxima) se associem positivamente ao desempenho no WOD Fran, considerando ainda que o sexo e a experiência de treino poderão influenciar a magnitude dessas associações.
- Estudo 3: a hipótese de que o sexo e a experiência de treino atuam como confundidores das relações entre variáveis fisiológicas e biomecânicas e o desempenho foi sustentada por estudos que demonstraram diferenças entre homens e mulheres, bem como entre níveis de experiência competitiva, nas respostas ao exercício de alta intensidade (Dexheimer et al., 2019; Fernández-Fernández et al., 2022; Schlegel & Křehký, 2022). Gerou-se a hipótese de que o sexo e a experiência de treino modulam as associações entre variáveis fisiológicas (VO_2 , ventilação, lactato) e biomecânicas (potência, fadiga neuromuscular) com o tempo de execução num WOD padronizado.

A confirmação, ou eventual refutação, das hipóteses propostas permitirá clarificar as relações entre variáveis fisiológicas, biomecânicas e o desempenho no CrossFit, contribuindo para uma compreensão mais integrada das exigências desta modalidade. Para além do seu contributo teórico, esta investigação poderá fornecer orientações práticas para a prescrição e monitorização do treino, sustentadas em evidência científica, e apoiar a individualização das estratégias de preparação física em função das características dos praticantes. Assim, a presente tese pretende não apenas aprofundar o conhecimento sobre os determinantes do desempenho de CrossFit, mas também promover a aplicação desse conhecimento em contextos reais de treino e competição.

Descrição dos Estudos

Estudo 1 – Revisão Sistemática

Foram incluídos uma panóplia de estudos que analisaram as exigências fisiológicas e biomecânicas do CrossFit em praticantes recreativos e atletas de competição. A pesquisa

foi realizada nas bases de dados da PubMed/MEDLINE, Web of Science e Scopus. Identificaram-se 19 estudos que reportaram respostas cardiovasculares, metabólicas e neuromusculares associadas ao treino e competição em CrossFit. Os resultados mostraram que os WODs induzem valores elevados de lactato sanguíneo (8-15 mmol·L⁻¹), frequência cardíaca próxima do máximo (>90% da frequência cardíaca máxima) e consumo máximo de oxigênio frequentemente superior a 80% durante o esforço. Do ponto de vista biomecânico, a força dinâmica máxima (1RM), a potência do salto vertical e a velocidade de movimento surgem como indicadores amplamente utilizados para caracterizar o perfil dos praticantes de CrossFit. No entanto, verificou-se grande heterogeneidade metodológica, ausência de consenso sobre os principais determinantes do desempenho e escassa consideração de variáveis moderadoras como sexo ou níveis de experiência de treino. Estes resultados reforçam a necessidade de estudos que integrem dimensões fisiológicas e biomecânicas em contextos aplicados.

Estudo 2 – Preditores fisiológicos e biomecânicos do desempenho

Participaram quinze praticantes de CrossFit treinados (8 homens; 7 mulheres; 27.7 ± 4.6 anos), classificados em iniciados (n = 7) e experientes (n = 8). Foram avaliados parâmetros antropométricos, de força dinâmica máxima (1RM estimado no agachamento, supino e peso morto), potência (salto vertical) e capacidade cardiorrespiratória (VO₂máx, ventilação e frequência cardíaca). O desempenho foi medido pelo tempo de execução do WOD “Fran” (21-15-9 thrusters e pull-ups realizados no menor tempo possível). Os resultados mostraram que os atletas do sexo masculino apresentaram valores superiores de massa corporal, massa muscular, força dinâmica máxima e capacidade aeróbia relativamente às atletas femininas ($p < 0.01$). Os atletas mais experientes completaram o WOD Fran significativamente mais rápido do que os iniciados, apesar de apresentarem perfis fisiológicos semelhantes, o que sugere que a experiência de treino poderá influenciar o desempenho, sobretudo através da proficiência técnica e da gestão de esforço. As análises correlacionais (Spearman ρ) revelaram associações moderadas e negativas entre o tempo total do WOD e as variáveis de força máxima, nomeadamente no agachamento ($\rho = -0.54$), no peso morto ($\rho = -0.56$) e no supino ($\rho = -0.65$). Contudo, nenhuma destas correlações permaneceu estatisticamente significativa após as correções de Holm e FDR. Estes resultados indicam que a força dinâmica máxima poderá contribuir para o desempenho no WOD “Fran”, embora as evidências devam ser interpretadas como exploratórias e careçam de confirmação em amostras maiores e estatisticamente mais robustas.

Estudo 3 – Determinantes fisiológicas e biomecânicas com análise de confundidores

Na mesma amostra de quinze praticantes de CrossFit (8 homens; 7 mulheres), foram recolhidas respostas fisiológicas e neuromusculares antes, durante e após a execução do WOD “Fran”. As medições incluíram concentrações de lactato sanguíneo, consumo de oxigênio, ventilação, frequência cardíaca, percepção subjetiva de esforço (PSE) e variação no desempenho de saltos verticais com e sem contramovimento. O tempo médio de execução foi de 422.1 ± 173.2 s (200–840 s). O melhor desempenho associou-se a maiores valores de VO_2 médio ($r = -0.60$, $p = 0.017$), maior ventilação média ($r = -0.58$, $p = 0.021$), maior potência de salto pré-WOD (salto com contramovimento, $r = -0.62$, $p = 0.014$) e maior acumulação de lactato pós-WOD ($r = -0.54$, $p = 0.036$). A análise por subgrupos revelou que os homens apresentaram melhores tempos e maiores respostas ventilatórias e neuromusculares, enquanto nas mulheres observaram-se maiores níveis de PSE e maior decréscimo na potência de salto com contramovimento. Os praticantes experientes completaram o WOD significativamente mais rápido do que os iniciantes, mas não apresentaram diferenças substanciais nas respostas fisiológicas agudas, sugerindo que a experiência competitiva poderá contribuir para uma maior eficiência técnica e regulação do esforço. Estes resultados reforçam a natureza multifatorial do desempenho no WOD “Fran” e sugerem que sexo e experiência de treino atuam como fatores moduladores das respostas fisiológicas e neuromusculares.

Conclusão Geral e Futuras Linhas de Investigação

O resultado global da presente tese de doutoramento sugere que o desempenho no CrossFit pode ser influenciado por uma interação entre variáveis fisiológicas e biomecânicas, afetadas por características individuais, como o sexo e a experiência de treino. A revisão sistemática evidenciou que os WODs impõem elevadas exigências cardiovasculares, metabólicas e neuromusculares, mas revelou ausência de consenso sobre os principais preditores de performance e escassa consideração de fatores confundidores. O primeiro estudo indicou que a força dinâmica máxima e a potência tendem a associar-se a melhores tempos de execução nos homens, enquanto nas mulheres as variáveis aeróbias e de força dinâmica máxima nos membros superiores poderão ter maior relevância.

Verificou-se ainda que a experiência de treino contribui para melhores tempos de execução do WOD “Fran”, provavelmente através de maior proficiência técnica e eficiência na gestão de esforço, e não por diferenças fisiológicas marcadas. Entre as associações moderadas e exploratórias, nenhuma se manteve significativa após as correções de Holm e FDR, sugerindo que os efeitos observados devem ser interpretados com cautela e confirmados em amostras maiores. O segundo estudo que variáveis fisiológicas, como o VO₂ médio, a ventilação e a acumulação de lactato, bem como indicadores de prontidão neuromuscular pré-WOD — refletidos pela potência muscular antes do exercício — se associaram de forma moderada a melhor desempenho, com padrões distintos entre sexos e níveis de experiência de treino. Estes resultados reforçam a noção de que o desempenho no CrossFit é multifatorial, sendo influenciado por fatores fisiológicos, biomecânicos e de prontidão individual. Além disso, o sexo e a experiência de treino atuam como moduladores das repostas ao treino de CrossFit.

Assim, esta tese representa um avanço importante na compreensão dos possíveis determinantes do desempenho em CrossFit, oferecendo uma visão integrada que combina síntese de literatura com evidência experimental aplicada. Em termos práticos, os resultados sugerem que programas de treino de CrossFit devem considerar simultaneamente parâmetros fisiológicos e biomecânicos, mas também adaptar a prescrição em função do sexo e experiência de treino do praticante. Para treinadores e atletas, significa que homens podem beneficiar de estratégias focadas na força dinâmica máxima e na potência, enquanto mulheres parecem mais condicionadas pela manutenção do desempenho sob fadiga e pela percepção subjetiva de esforço, sugerindo a importância de estratégias que melhorem a tolerância à fadiga. Além disso, a experiência de treino deve ser entendida não apenas como tempo acumulado, mas também como fator crítico na proficiência técnica e na gestão de esforço durante WODs de elevada intensidade.

Apesar das contribuições apresentadas, futuros projetos de investigação devem procurar colmatar as limitações identificadas, explorando de forma mais robusta as relações entre determinantes fisiológicos, biomecânicos e características individuais em diferentes contextos de CrossFit. Nesse sentido, sugerem-se algumas linhas de investigação a desenvolver:

- i) Analisar amostras maiores e mais diversificadas, incluindo atletas de elite e/ou recreativos, para confirmar os determinantes do desempenho e aumentar a generalização dos resultados;

- ii) Comparar diferentes tipos de WODs (p, ex., força, metabólicos, mistos) para identificar se os preditores de desempenho se mantêm ou variam em função da estrutura da tarefa;
- iii) Investigar, através de desenhos longitudinais, como o treino específico do CrossFit modifica os preditores fisiológicos e biomecânicos ao longo do tempo;
- iv) Examinar o impacto da experiência acumulada em estratégias de pacing, economia de movimento e eficiência técnica, de modo a clarificar como este fator contribui para a performance, independentemente das capacidades físicas;
- v) Explorar diferenças entre sexos em respostas de fadiga aguda (neuromuscular, ventilatória e metabólica), de forma a fundamentar intervenções de treino mais individualizadas;
- vi) Desenvolver modelos preditivos integrativos que combinem medidas fisiológicas e biomecânicas para explicar de forma mais precisa a variabilidade entre indivíduos desempenho em CrossFit.

Abstract

Over the past decade, CrossFit has become established as both a popular form of high-intensity strength and conditioning training and a growing competitive sport. Despite its global diffusion, uncertainties remain regarding the main physiological and biomechanical determinants of performance, particularly when accounting for sex and training experience. This doctoral thesis aimed to provide an integrated analysis of CrossFit's physiological and biomechanical demands and to explore potential performance predictors in recreational athletes. Three studies were conducted: i) a systematic review on physiological and biomechanical demands; ii) an experimental analysis of the associations between physiological and biomechanical variables and WOD performance; and iii) an examination of how sex and training experience modulate these relationships. The findings indicated that WODs elicit high cardiovascular, metabolic, and neuromuscular demands, yet the literature remains heterogeneous and lacks consensus on key performance determinants. Data revealed moderate, exploratory associations between performance and variables such as maximal strength, jumping power, ventilation, oxygen consumption, and post-exercise blood lactate, with these relationships differing by sex and experience. Men appeared to rely more on strength and power, whereas women were more influenced by physiological responses and perceived exertion. Training experience was linked to faster completion times, likely due to greater technical proficiency and effort regulation. Overall, the results highlight the multifactorial nature of CrossFit performance and the need for individualized training approaches based on physiological, biomechanical, and experiential characteristics.

Keywords

CrossFit; high-intensity training; physiology; biomechanics; performance; sex; training experience

Table of Contents

Declaração de Integridade.....	iii
Dedication.....	v
Acknowledgments	vii
List of Publications and Communications	ix
Resumo	xi
Resumo Alargado	xiii
Abstract.....	xxiii
List of Figures	xxvii
List of Tables	xxix
List of Acronyms	xxxii
Chapter 1. General Introduction.....	1
Chapter 2. Literature Review.....	7
Study 1. Biomechanical and Physiological Demands of CrossFit: A Systematic Review	7
Chapter 3. Experimental Studies	35
Study 2. Exploratory Analysis on Physiological and Biomechanical Correlates of Performance in the CrossFit Benchmark Workout Fran.....	35
Study 3. Exploratory Analysis of Physiological and Biomechanical Determinants of CrossFit Benchmark Workout Performance: The Role of Sex and Training Experience	55
Chapter 4. General Discussion	75
Chapter 5. Overall Conclusions	79
Chapter 6. Suggestions for Future Research.....	81

Chapter 7. References 83

Appendix.....109

List of Figures

Chapter 2, Study 1

Figure 1. Literature searching flowchart.....15

Chapter 3, Study 2

Figure 1. Schematic representation of the experimental protocol. 39

Figure 2. Pearson correlation heatmap among anthropometric, strength, aerobic, experience, and performance variables ($n = 15$). Stronger negative values (blue) indicate faster Fran completion times, whereas positive values (red) reflect slower performance. Only the lower triangle is shown for clarity. Although several raw correlations with WOD time appeared moderate in magnitude, none remained statistically significant after Holm–Bonferroni or FDR correction for multiple testing. 50

Chapter 3, Study 3

Figure 1. Standardized execution of squat jump (left) and countermovement jump (right) tests. 60

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). 63

Figure 3. Boxplots (median, interquartile range, minimum–maximum, and outliers) of lean mass (kg) and ventilatory response (ΔV_e , $L \cdot \text{min}^{-1}$) stratified by sex. Asterisks indicate significant differences (* $p < 0.05$; *** $p < 0.001$). 66

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)..... 67

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). 68

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.....69

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.69

List of Tables

Chapter 2. Study 1

Table 1. Search terms and keywords used in the screening procedures of the systematic review.....	12
Table 2. Study quality analysis using the Joanna Briggs Institute (JBI) Critical Appraisal Checklist for Analytical Cross-Sectional Studies.....	16
Table 3. Study quality analysis using the PEDro scale.....	16
Table 4a. Biomechanical variables of evaluation of CrossFit performance.....	18
Table 4b. Biomechanical variables of evaluation of CrossFit performance.....	19
Table 5a. Physiological variables of evaluation of CrossFit performance.....	24
Table 5b. Physiological variables of evaluation of CrossFit performance.....	25

Chapter 3. Study 2

Table 1. Sex comparisons are presented with effect sizes and 95% confidence intervals.....	46
Table 2. Between-sex differences in key anthropometric, strength, and cardiorespiratory variables in trained CrossFit athletes ($n = 15$). Values are presented as mean \pm standard deviation. Group comparisons were performed using the Mann–Whitney U test, with p-values adjusted for multiple testing using the Holm procedure. Only variables showing significant differences or high physiological/biomechanical relevance are reported. VO_{2max} : maximal oxygen uptake; VE_{max} : maximal minute ventilation.....	48
Table 3. Bivariate and partial correlations between Fran workout completion time and key anthropometric, strength, and body-composition variables in trained CrossFit athletes ($n = 15$). Values are Pearson’s correlation coefficient (r) and Spearman’s rank correlation coefficient (ρ) with corresponding p-values; partial r represents Pearson correlations adjusted for years of CrossFit practice. Holm and false discovery rate (FDR) procedures were applied to adjust for multiple comparisons. Negative coefficients indicate that higher values of the predictor variable are associated with faster completion times (better performance).....	49

Chapter 3. Study 3

Table 1. Descriptive analysis for total sample WOD performance time and variations (Δ) of physiological and neuromuscular responses.65

Appendix

Table 1. Strength and mechanical performance during resistance exercises at 80% of 1RM, compared by sex.109

List of Acronyms

ACSM	American College of Sports Medicine
AMRAP	As Many Repetitions As Possible Máximo de repetições possíveis
BS	Back Squat Agachamento com barra livre
BP	Bench Press Supino
FRAN	Benchmark Workout “Fran” WOD de referência “Fran”
La	Blood Lactate Concentration Concentração de lactato sanguíneo
BM	Body Mass Massa corporal
BMI	Body Mass Index Índice de massa corporal
Δ La	Change in Blood Lactate Variação da concentração de lactato
Δ La	Change in Blood Lactate Concentration Variação da concentração de lactato sanguíneo
Δ CMJ	Change in Countermovement Jump Variação no salto com contramovimento
Δ HR	Change in Heart Rate Variação da frequência cardíaca
Δ HRV	Change in Heart Rate Variability Variação da variabilidade da frequência cardíaca
Δ VO ₂	Change in Oxygen Uptake Variação do consumo de oxigénio
Δ VO ₂	Change in Oxygen Uptake Variação no consumo de oxigénio
Δ SJ	Change in Squat Jump Variação no Agachamento com Salto
Δ Ve	Change in Ventilation Variação da ventilação
CMJ	Countermovement Jump Salto com contramovimento
DL	Deadlift Peso morto
EMG	Electromyography Eletromiografia
HR	Heart Rate Frequência cardíaca
HRV	Heart Rate Variability Variabilidade da frequência cardíaca
HIT	High-Intensity Training Treino de alta intensidade
HIIT	High-Intensity Interval Training Treino intervalado de alta intensidade
IMU	Inertial Measurement Unit Unidade de medição inercial
HR _{max}	Maximal Heart Rate Frequência cardíaca máxima
VO _{2max}	Maximal Oxygen Uptake Consumo máximo de oxigénio
MD	Mean difference
HR _{mean}	Mean Heart Rate Frequência cardíaca média
VO _{2mean}	Mean Oxygen Uptake Consumo médio de oxigénio
MPV	Mean Propulsive Velocity Velocidade propulsiva média

VO ₂ min	Minimal Oxygen Uptake Consumo mínimo de oxigénio
1RM	One-Repetition Maximum Uma repetição máxima
VO ₂	Oxygen Uptake Consumo de oxigénio
PSE	Perceção subjetiva de esforço
RPE	Rating of Perceived Exertion Escala de perceção subjetiva de esforço
%1RM	Relative load Carga relativa
MVP2	Second Measure of Mean Propulsive Velocity Segunda medição da velocidade propulsiva média
SJ	Squat Jump Agachamento com Salto
SD	Standard Deviation Desvio padrão
SPSS	Statistical Package for the Social Sciences Pacote estatístico SPSS
VE	Ventilation Ventilação
WOD	Workout of the Day Treino do dia
WHO-5	World Health Organization Well-Being Index;

Chapter 1. General Introduction

Over the past two decades, CrossFit has emerged as one of the fastest-growing exercise modalities worldwide, with thousands of affiliated gyms and millions of practitioners distributed across all continents (Dominski et al., 2022; Mehrab et al., 2022). Conceptually, CrossFit is framed within the paradigm of high-intensity strength and conditioning training, defined as constantly varied of movements performed at high intensity (Cosgrove et al., 2019; Glassman, 2007). These movements typically integrate elements from Olympic weightlifting, gymnastics, and metabolic conditioning, executed under high-intensity conditions and frequently performed in a state of accumulated fatigue (Claudino et al., 2018).

At the heart of CrossFit lies the Workout of the Day (WOD), a multimodal training session that varies daily in load, duration, and modality to stimulate broad adaptations across fitness domains (Cavedon et al., 2020; Dominski et al., 2021). This structure draws on established principles of training, particularly specificity, overload, and individualization, while incorporating methodological variability (often referred to as “variance”) to promote comprehensive physical preparedness and prevent monotony (Feito et al., 2018; Meier et al., 2023; Pritchard et al., 2020). The principle of scalability further ensures that training loads and movement complexity can be adjusted to accommodate both beginners and advanced athletes within the same session.

A distinctive feature of CrossFit is its dual identity as both a health-oriented training methodology and a competitive sport (Dominski et al., 2020; Dominski et al., 2022). For general populations, it is adopted to improve health, body composition, and overall fitness (Aravena-Sagardia et al., 2025; Eather et al., 2016; Schile et al., 2023). At the same time, CrossFit has gained international recognition as a sport through the CrossFit Games and regional competitions, where athletes are evaluated on their ability to complete standardized WODs in the shortest time possible or to maximize repetitions within a given time frame (Butcher et al., 2015; Martínez-Gómez et al., 2019). This dual nature enriches the scientific relevance of CrossFit, making it a unique model for studying the acute and chronic physiological, neuromuscular, and biomechanical responses to multimodal high-intensity exercise.

Accumulating evidence from narrative and systematic reviews indicates that CrossFit training elicits concurrent adaptations across multiple fitness domains, including strength, hypertrophy, power, muscular endurance, and cardiorespiratory fitness

(Claudino et al., 2018; Dominski et al., 2021; Meier et al., 2023). Despite this broad adaptive potential, the determinants of WOD performance remain a subject of ongoing debate (Tibana et al., 2021). Observational studies have identified several potential predictors of performance, spanning neuromuscular variables (e.g., one-repetition maximum, vertical jump performance, power output) and physiological markers (e.g., maximal oxygen uptake, ventilatory responses, blood lactate) (Butcher et al., 2015; Martínez-Gómez et al., 2019; Mangine et al., 2020; Zeitz et al., 2020). However, no consensus has been reached regarding their relative contribution to overall performance.

A first observation derived from the literature is that most studies have examined physiological or biomechanical dimensions in isolation, without systematically integrating both domains to understand CrossFit performance fully (Butcher et al., 2015; Martínez-Gómez et al., 2019; Mangine et al., 2020; Zeitz et al., 2020; Claudino et al., 2018). This methodological fragmentation limits the global interpretation of the demands imposed by training and competition, often leading to contradictory results. Therefore, it becomes relevant to synthesize the existing evidence to identify the most frequently studied parameters, the most consistent methodologies, and the research gap that justifies further investigation.

Although some studies have examined sex- or experience-related differences in CrossFit performance (Dexheimer et al., 2019; Schlegel & Křehký, 2022), most research has analyzed physiological or biomechanical factors in isolation (Butcher et al., 2015; Martínez-Gómez et al., 2019; Mangine et al., 2020; Zeitz et al., 2020; Rios et al., 2024), without integrating both domains or accounting for how individual characteristics may modulate performance. Biological differences between men and women, particularly in muscle mass, ventilatory threshold, and fatigue resistance, as well as the role of accumulated training experience in technical efficiency and pacing strategies, suggest that performance in WODs may be determined by distinct predictors depending on the subgroup analyzed (Dexheimer et al., 2019; Schlegel & Křehký, 2022; Zeitz et al., 2020). However, to date, few studies have explored these variables comparatively or predictively, limiting the practical applicability of the available evidence for coaches and athletes. Thus, experimental studies are warranted to identify which biomechanical and physiological predictors determine WOD performance and how these vary according to sex and training experience.

It is also noteworthy that several studies have examined physiological and neuromuscular responses to CrossFit workouts, and few have simultaneously monitored

their integrated time course during a standardized benchmark. Study 3, therefore, aimed to characterize the acute physiological and biomechanical responses elicited by a standardized WOD (Fran), including changes in ventilatory dynamics, oxygen uptake, blood lactate, and neuromuscular performance (jump height and power). Rather than identifying long-term predictors of performance, this study sought to determine the extent to which a benchmark CrossFit workout acutely perturbs physiological homeostasis and neuromuscular function, thereby providing insight into how such sessions challenge the body's regulatory systems.

Objectives and Hypotheses

Considering these aspects, the overall aim of this doctoral thesis was to develop an integrated understanding of the physiological and biomechanical determinants of CrossFit performance and acute responses. Specifically, the thesis sought to clarify how these domains interact and how individual characteristics, particularly sex and training experience, modulate these relationships.

To achieve this aim, three specific objectives were defined:

- Study 1: To conduct a systematic review of the literature on the physiological and biomechanical demands of CrossFit training and competition, identifying the main parameters investigated, the degree of methodological consistency, and existing research gaps.
- Study 2: To examine, in an experimental context, the associations between physiological and biomechanical variables and performance in a benchmark WOD (Fran), while exploring potential differences related to sex and training experience.
- Study 3: To characterize the acute physiological and neuromuscular responses induced by a standardized WOD and to determine how these responses differ according to sex and training experience, thereby clarifying the acute effects of CrossFit exercise on the body's physiological and biomechanical systems.

Based on the theoretical and empirical considerations discussed, the following hypotheses were formulated:

General hypothesis:

- CrossFit performance and acute physiological and biomechanical responses are determined by the interaction between these factors, which are further modulated by individual characteristics such as sex and training experience.

Specific hypotheses:

- i) The literature will reveal high cardiovascular, metabolic, and neuromuscular demands associated with CrossFit. On the other hand, the literature will reveal lack of integration between physiological and biomechanical analyses and limited consideration of individual factors;
- ii) In a benchmark WOD, physiological and biomechanical variables (e.g., maximal strength, power, ventilatory, and metabolic parameters) will show moderate associations with performance, with differences expected between men and women and between more and less experienced practitioners;
- iii) A standardized WOD will elicit significant acute perturbations in physiological (ventilation, oxygen uptake, lactate) and neuromuscular (jump performance, power) measures, with sex and training experience influencing the magnitude of these responses.

Together, these objectives and hypotheses establish a coherent progression, from a descriptive synthesis of the existing literature to applied experimental analysis, culminating in a mechanistic understanding of the acute physiological and biomechanical responses that characterize CrossFit training.

Given the considerations mentioned above, the general purpose of the present Ph.D. thesis was to analyze the physiological and biomechanical determinants of CrossFit performance, while considering the moderating role of sex and training experience. To achieve this purpose, a sequence of studies was defined, which makes up the following thesis structure:

- Chapter 2 presents a systematic review of the literature that synthesizes the physiological and biomechanical demands of CrossFit training and competition, highlighting the main parameters assessed, methodological heterogeneity, and the existing research gaps (Study 1).
- Chapter 3 compiles the first experimental study, which examined the physiological and biomechanical predictors of performance in a benchmark WOD (Fran) and compared differences based on sex and training experience. (Study 2).
- Chapter 4 presents the second experimental study, which characterized the acute physiological and neuromuscular responses to a standardized WOD, analyzing how these responses differed according to sex and training experience (Study 3).

Following this, Chapter 5 integrates the findings across studies in a general discussion, critically interpreting the results in the context of existing literature. Chapter 6 presents the main conclusions of this thesis, and Chapter 7 provides limitations and outlines directions for future research.

Chapter 2. Literature Review

Study 1. Biomechanical and Physiological Demands of CrossFit: A Systematic Review

Abstract

CrossFit's popularity has increased as an effective training program for physical fitness. The volume of published literature suggests a continuous effort to understand and optimize CrossFit training protocols. Therefore, this study aimed to analyze scientific literature findings related to CrossFit's biomechanical and physiological demands via a systematic review. Systematic searches were conducted on PubMed, Web of Science, ScienceDirect, Scopus, and SciELO databases for articles reporting the effects of CrossFit training. Following the PRISMA guidelines, nineteen studies ($n = 537$ participants) examined the use of biomechanical and/or physiological variables in CrossFit performance. This review considered the one-repetition maximum, the countermovement jump, peak power, and movement technique as biomechanical variables most often used in literature. The physiological variables included blood lactate, maximal oxygen uptake, heart rate variability, and the rating of perceived exertion. These variables accurately measured strength, aerobic, and anaerobic capacity, along with fatigue in training sessions and competitions. CrossFit training was shown to improve maximal oxygen uptake, muscle strength, hypertrophy, and muscular endurance while also inducing physiological stress. Strength and power variables correlated strongly with CrossFit performance, but movement technique and postural control also played significant roles. The combination of aerobic and anaerobic elements within CrossFit enhanced cardiovascular fitness and anaerobic capacity, reinforcing effectiveness when appropriately managed.

Keywords: fitness, physical performance, biomechanics, physiology, high-intensity interval training

Introduction

The increasing popularity of CrossFit as a sport has likely contributed to a significant increase in scientific research (Dominski et al., 2021; Meier et al., 2023; Rodríguez et al., 2022). The exponential growth of CrossFit is unprecedented and signified by over 15,000 CrossFit-affiliated gyms worldwide and the global recognition as a “fitness sport” (Dexheimer et al., 2019; Dominski et al., 2021; Sauvé et al., 2024), with over 5 million athletes worldwide engaging in CrossFit-based training (Gianzina and Kassotaki, 2019; Meier et al., 2023). A review of the available literature reveals a substantial number of publications addressing various aspects of CrossFit (Claudino et al., 2018; Jacob et al., 2020; Mehrab et al., 2023; Meier et al., 2023), including exercise programming (Ambroży et al., 2022; Knapik, 2015; Oliver-López et al., 2024), injury prevention (Klimek et al., 2018; Nicolay et al., 2022; Shim et al., 2023), performance optimization (Shaw and Sergent, 2019; Sousa et al., 2016; Tafuri et al., 2019), and metabolic demands during different workout configurations (Feito et al., 2019; Gómez-Landero and Frías-Menacho, 2020; Maté-Muñoz et al., 2017).

CrossFit methodology is widely classified under high-intensity training, which is defined by the use of multi-joint movements performed at high intensity and incorporating both aerobic and resistance exercise modalities (Feito et al., 2019; Heinrich et al., 2015). Indeed, CrossFit is recognized as a high-intensity sport involving powerlifting and gymnastics movements using heavy loads and maximal efforts (Dominski et al., 2021; Fisker et al., 2017; Tibana et al., 2018). Therefore, improvements in physical fitness are based on strength and conditioning training using complex, powerful, and continuous movements that stimulate practitioners’ metabolism exponentially (Maté-Muñoz et al., 2017; Schlegel, 2020; Tibana et al., 2021). Due to the high intensity of the exercises used and short or no rest periods, reduced movement velocity during exercise (i.e., fatigue) is considered a determining factor (Faelli et al., 2020; Maté-Muñoz et al., 2017). In the literature, fatigue has been defined as an involuntary loss of muscle strength across successive repetitions, leading to a notable reduction in movement velocity during exercise execution (Banyard et al., 2017; Maté-Muñoz et al., 2017; Sánchez-Medina and González-Badillo, 2011). Given that CrossFit is characterized by highly varied workouts often performed near or to the point of muscular failure, understanding patterns of velocity loss, commonly used as a proxy for neuromuscular fatigue (González-Badillo et al., 2022; Sánchez-Medina and González-Badillo, 2011), may serve as a valuable indicator for performance optimization, injury prevention, and training load monitoring.

Generally, training sessions are organized as daily sessions named workout of the day (WOD). These WODs are typically scheduled to perform the exercises as fast as possible, i.e., “for time” (FT), or to perform the maximum number of repetitions or rounds in an established time, i.e., “as many rounds as possible” (AMRAP) (Glassman, 2010; Menargues-Ramírez et al., 2022). The athletes’ progression in CrossFit could be measured through these sessions, provided that the execution conditions are controlled (including exercises, loads, repetitions, or execution time). However, due to the constant variations introduced in each WOD, it is important to track changes through periodic monitoring of the performance of specific exercises. Therefore, benchmark WODs are established to assess the progress of some workouts by comparing the number of repetitions and time for completion over time and between athletes (Glassman, 2003). For example, the benchmark WOD “Fran” consists of performing 21-15-9 repetitions for time of pull-ups and thrusters, and “Grace” is a set of 30 clean and jerks to complete for time (Glassman, 2003). In this regard, previous studies have investigated the influence of different factors on the performance in benchmark WODs, in ‘CrossFit Open’ workouts, or the placement in the ‘CrossFit Games’ (Carreker and Grosicki, 2020; Fernández-Fernández et al., 2015; Kliszczewicz et al., 2014; Maté-Muñoz et al., 2017). Evidence-based recommendations for effective and specific training programming could be developed by identifying performance predictors, leading to optimal competitive performance.

Several studies have investigated biomechanical aspects of CrossFit exercises, focusing on movement patterns, joint loading, and muscular activation (Cejudo, 2022; Ferreira et al., 2020; Martínez-Gómez et al., 2019). At the core of these considerations there are joint kinematics which describe movement patterns of joints during various exercises, notably Olympic lifts. Understanding these patterns is crucial, as they have been demonstrated to impact both performance outcomes and injury risk among CrossFit practitioners (Butcher et al., 2015b; Naderi et al., 2025). For instance, Butcher et al. (2015b) observed that biomechanical efficiency tended to decline under fatigue during high-repetition strength exercises, with a corresponding decrease in performance.

Beyond joint movement, neuromuscular activation also plays a vital role in biomechanical efficiency during CrossFit. Adequate levels of muscular strength are essential for executing complex, multi-joint movements such as Olympic lifts. In this context, Martínez-Gómez et al. (2019) demonstrated strong correlations between lower-body power, as measured by full squat performance, and success in CrossFit workouts. Their findings suggest that biomechanical proficiency not only supports technical

execution but also serves as a key determinant of performance outcomes. This evidence reinforces the relevance of biomechanical assessment for guiding both the training program design and performance monitoring.

Additionally, biomechanical demands in CrossFit extend to aspects such as load management and consistency of the bar path during lifting tasks (Polydorou et al., 2024). Equipment choices can also play a role in optimizing movement (Meyer et al., 2017). For example, Waryasz et al. (2016) found that wearing weightlifting shoes with elevated heels could modify joint angles during lifts, thereby reducing shear stress on the spine. These biomechanical insights inform evidence-based decisions regarding gear selection and technique adjustments, ultimately aiming to improve performance while mitigating injury risk.

Additionally, studies exploring the physiological demands of CrossFit training have examined factors such as cardiovascular responses, energy expenditure, and muscle fatigue (Faelli et al., 2020; Mangine et al., 2020). The published literature suggests a continuous effort to understand and optimize CrossFit training protocols to improve performance by delaying fatigue appearance (Mangine et al., 2023; Weisenthal et al., 2014). According to Meyer et al. (2017), one of the most important factors for improving the ability to resist loss of strength or velocity is the proper manipulation of training load and volume. Considering this, WODs often involve a high volume of repetitions across different exercises, which could promote rapid fatigue, particularly when training volume and intensity are not adequately periodized, which may result in a decline in movement quality and an increased risk of injury (Gardiner et al., 2020; Mehrab et al., 2023).

Despite the extensive research conducted over the last decade on CrossFit, there is still no consensus on the key factors that determine performance or on the mechanical and metabolic responses to different WODs. This knowledge could allow for improved training processes for CrossFit practitioners. Therefore, in an attempt to synthesize existing information and continue to improve the scientific research in CrossFit, this systematic review aimed to assess biomechanical and physiological variables and demands related to CrossFit training.

Methods

Study design

To guide the organization of findings, we applied a thematic analysis that grouped studies into two primary domains: biomechanical and physiological. This categorization was informed by the predominant outcomes and assessment tools used across literature. Studies classified as biomechanical primarily investigated variables such as joint kinematics, movement velocity, force production, power output, and muscle activation, often employing technologies such as motion capture, electromyography (EMG), and force platforms (Butcher et al., 2015b; Cejudo, 2022; Martínez-Gómez et al., 2019; Maté-Muñoz et al., 2018; Yüksel et al., 2018). In contrast, physiological studies focused on aspects related to the internal load and fatigue responses, including maximal oxygen uptake (VO_{2max}), blood lactate concentration, heart rate variability (HRV), and the rate of perceived exertion (RPE) (Faelli et al., 2020; Schlie et al., 2023; Tibana et al., 2018; Zeitz et al., 2020). The rationale for these thematic divisions aligns with established distinctions in the literature between mechanical and metabolic demands in training (Bachero-Mena and González-Badillo, 2021; Di Michele et al., 2012; Maté-Muñoz et al., 2018; Rios et al., 2024). However, the specific structure of sub-themes in this review was developed inductively, based on the objectives and reported outcomes of the included studies. For instance, outcomes such as the countermovement jump (CMJ) and one-repetition maximum (1RM) were grouped under strength and power performance within the biomechanical dimension. To synthesize the existing information, we considered the biomechanical and physiological aspects discussed above to identify the performance variables in CrossFit training and competition.

Search strategy

This systematic literature search followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021). The review protocol was prospectively registered in the International Platform of Registered Systematic Reviews (INPLASY) under the registration number INPLASY202560108. The protocol is publicly available at <https://doi.org/10.37766/inplasy2025.6.0108>. Studies were retrieved from PubMed, Web of Science, ScienceDirect, Scopus, and SciELO databases. These databases were selected to ensure comprehensive coverage of both international and regional literature relevant to the physiological and biomechanical aspects of CrossFit. While PubMed, Scopus, and Web of Science

databases are widely recognized for indexing peer-reviewed scientific publications in health and sports science, ScienceDirect was included due to its accessibility to full-text articles from journals that frequently publish exercise science research. SciELO was added to capture relevant literature from Latin American sources that might not be indexed in other major databases. However, it was acknowledged that not including databases such as SPORTDiscus, Embase, or Google Scholar, might have introduced database selection bias. This limitation should be considered when interpreting the completeness of the included evidence.

Studies were searched using a Boolean string with specific keywords (Table 1). The literature search was performed between December 2023 and February 2024 by an independent author and checked by a second author (P.F.). These procedures were conducted according to the recommended PRISMA guidelines (Page et al., 2021).

Table 1. Search terms and keywords used in the screening procedures of the systematic review.

Search term	Keywords
Population	1 “CrossFit” OR “high functional training” OR “functional fitness”
Intervention	2 “effects” OR “training effects” OR “training strategies”
Comparison/outcomes	3 Physiological set: “training load” OR “external training load” OR “internal training load” OR “physical performance” OR “physiological performance” OR “physical response” OR “physical demands” OR “physiological response” OR “physiological demands” OR “activity profile” OR “workload” OR “loading” OR “athletic performance” OR “sports performance” OR “velocity loss” OR “movement speed loss” OR “peak power” OR “power” OR “propulsive velocity” OR “MPV” OR “heart rate” OR “perceived exertion” OR “lactate” OR “acid lactic” OR “volume of oxygen consume” OR “VO2max” OR “metabolic power” OR “energy cost” OR “high intensity” OR “conditioning” OR “fitness” OR “biomechanics” OR “kinetic” OR “kinematic” OR “physiology”
Boolean syntax	4 (((#4) AND #3) AND #2) AND #1

Inclusion criteria

The following inclusion criteria were applied: i) peer-reviewed studies with experimental (randomized and non-randomized trials), observational (cohort, case-control), or cross-sectional designs investigating the effects of CrossFit; ii) studies involving adult CrossFit practitioners aged ≥ 18 years; iii) studies conducted with healthy adults, athletes or individuals with specific health conditions actively engaged in CrossFit training; iv) studies assessing physiological or biomechanical variables following CrossFit training or participation, including both intervention-based and descriptive designs (e.g., studies

measuring fatigue responses during benchmark WODs without a structured intervention); v) studies providing at least a partial description of the CrossFit program applied, such as training frequency, load, volume, duration, or types of exercise, even if not all training details were fully specified due to ecological or real-world research constraints; and vi) studies reporting quantitative outcomes related to physical fitness, performance, or physiological and biomechanical responses.

Data Extraction and Coding

To ensure transparency and methodological rigor, the screening and data extraction procedures were conducted following the PRISMA 2020 guidelines (Page et al., 2021). Two independent reviewers (A.M. and P.F.) screened the titles, abstracts, and full texts of all retrieved studies based on the predefined inclusion criteria. Any disagreements during the selection process were resolved through discussion, and when necessary, a third reviewer (D.L.M.) was consulted to reach consensus. Duplicate records were identified and removed using Microsoft Excel, supplemented by manual verification to ensure accuracy. Data extraction was also carried out independently by two reviewers and focused on the following categories: i) sample characteristics, the study design, and the competitive level; ii) performance-related outcomes including measurement variables, thresholds, and formulas; iii) references and foundational studies on which the included articles based their methodology; iv) methodological details such as study aims, experimental procedures, data collection methods, and statistical analysis. This structured and collaborative approach was intended to minimize bias, improve consistency, and strengthen the credibility of the review in line with established reporting standards (Page et al., 2021).

Study Quality Assessment

Two reviewers independently assessed the methodological quality of the included studies, with discrepancies resolved by consensus. For randomized controlled trials (RCTs), the Physiotherapy Evidence Database (PEDro) scale was applied. This tool consists of 11 items, with each item scored as either 0 or 1, yielding a maximum score of 10 (the first item is not included in the final score). Studies scoring ≥ 6 were considered of high quality, consistent with established cut-offs (García-Pinillos et al., 2017). For cross-sectional studies, the checklist “Joanna Briggs Institute (JBI) Critical Appraisal Checklist for Analytical Cross-Sectional Studies” was used. This checklist includes eight items evaluating aspects such as sample selection, validity of measurements, and

appropriateness of statistical analysis (Munn et al., 2023). Each item was rated as “yes”, “no”, “unclear”, or “not applicable”. Studies meeting six or more criteria were of moderate to high methodological quality. No studies were excluded based on methodological quality. Although formal inter-rater reliability (e.g., Cohen’s kappa) could not be calculated due to identical ratings across studies (McHugh, 2012), complete agreement (100%) was observed between reviewers. Any minor uncertainties were resolved through discussion to ensure consistency and transparency throughout the appraisal process.

Results

The results section follows a presentation based on study searching results, quality of the included studies, and performance indicators. The performance variables were subdivided into biomechanical and physiological.

Study Search Results

The search strategy found 151 articles (48 articles from PubMed, 31 from ScienceDirect, 17 from Scopus, 22 from Web of Science, and 33 from SciELO). Following full-text screening, 19 articles were included. The selection process is outlined in Figure 1, adhering to PRISMA guidelines. To conduct this review, the existing body of literature on CrossFit was first explored to gain a comprehensive understanding of the current research landscape. Based on this synthesis and the defining characteristics of CrossFit, the identified performance-related variables were organized into two overarching categories (physiological and biomechanical dimensions), reflecting how these aspects are commonly addressed in literature. In defining the main themes of this review, priority was given to elements of CrossFit training with strong theoretical and practical relevance for researchers, coaches, and athletes. These include: i) biomechanical variables that characterize movement patterns, joint loading, and mechanical demands during training and competition, and ii) physiological aspects related to muscular fatigue, metabolic stress, and key performance indicators.

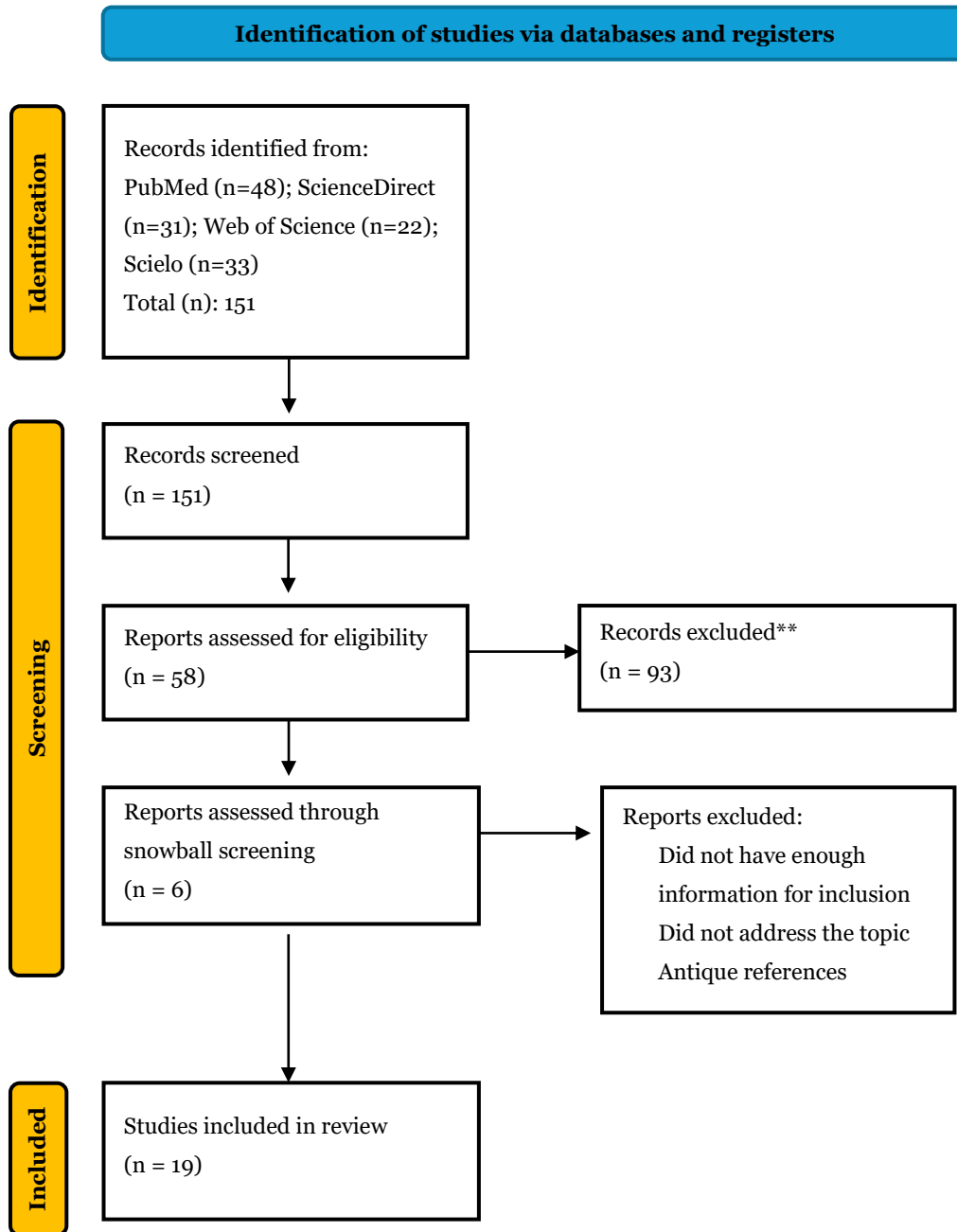


Figure 1. Literature searching flowchart.

Quality of the Included Studies

In the evaluation of methodological quality, the qualitative scores for 15 cross-sectional studies ranged from 6 (lowest quality) to 7 (highest quality) out of a maximum of 8 possible points in the JBI scale (Table 2). Fourteen studies received a score of 6, while one study had a score of 7. Regarding the experimental studies, four studies scored 9 (highest quality) out of 11 points on the PEDro scale (Table 3).

Table 2. Study quality analysis using the Joanna Briggs Institute (JBI) Critical Appraisal Checklist for Analytical Cross-Sectional Studies.

Authors	Q1	Q2	Q2	Q4	Q5	Q6	Q7	Q8	Total
Brogna et al. (2023)	Y	Y	Y	Y	N	N	Y	Y	6/8
Butcher et al. (2015a)	Y	Y	Y	Y	N	N	Y	Y	6/8
Butcher et al. (2015b)	Y	Y	Y	Y	N	N	Y	Y	6/8
Cejudo (2022)	Y	Y	Y	Y	N	N	Y	Y	6/8
Faelli et al. (2020)	Y	Y	Y	Y	N	N	Y	Y	6/8
Fernández-Fernández et al. (2015)	Y	Y	Y	Y	N	N	Y	Y	6/8
Ferreira et al. (2020)	Y	Y	Y	Y	N	N	Y	Y	6/8
Haynes and DeBeliso (2019)	Y	Y	Y	Y	N	N	Y	Y	6/8
Maia et al. (2019)	Y	Y	Y	Y	Y	N	Y	Y	7/8
Martínez-Gómez et al. (2019)	Y	Y	Y	Y	N	N	Y	Y	6/8
Maté-Muñoz et al. (2018)	Y	Y	Y	N	N	N	Y	Y	6/8
Maté-Muñoz et al. (2017)	Y	Y	Y	N	N	N	Y	Y	6/8
Sauvé et al. (2024)	Y	Y	Y	Y	N	N	Y	Y	6/8
Tibana et al. (2018)	Y	Y	Y	Y	N	N	Y	Y	6/8
Zeitz et al. (2020)	Y	Y	Y	Y	N	N	Y	Y	6/8

Q1: Were the criteria for inclusion in the sample clearly defined?; Q2: Were the study subjects and the setting described in detail?; Q3: Was the exposure measured in a valid and reliable way?; Q4: Were objective, standard criteria used for measurement of the condition?; Q5: Were confounding factors identified?; Q6: Were strategies to deal with confounding factors stated?; Q7: Were the outcomes measured in a valid and reliable way?; Q8: Was an appropriate statistical analysis used?; Y: yes (1 point); N: no (0 points)

Table 3. Study quality analysis using the PEDro scale.

Study criteria	Brandt et al. (2022)	Cosgrove et al. (2019)	Yüksel et al. (2018)	Schlie et al. (2023)
Eligibility criteria	Y	Y	Y	Y
Random allocation	Y	Y	Y	Y
Concealed allocation	Y	Y	Y	Y
Baseline comparability	Y	Y	Y	Y
Blinded participants	N	N	N	N
Blinded therapists	N	N	N	N
Blinded assessors	Y	Y	Y	Y
Adequate follow-up	Y	Y	Y	Y
Intention-to-treat analysis	Y	Y	Y	Y
Between-group comparisons	Y	Y	Y	Y
Point estimates and variability	Y	Y	Y	Y
Total score	9/11	9/11	9/11	9/11

Biomechanical Variables

The literature on biomechanical variables of CrossFit encompasses a wide range of studies focusing on the measurement and analysis of movement patterns, joint forces, and muscle activity during CrossFit exercises. Table 4 summarizes key biomechanical variables and their measurement tools.

Table 4a. Biomechanical variables of evaluation of CrossFit performance.

Authors	Design	Topic	Sample	Analysis	Main Findings
Brandt et al. (2022)	Randomized controlled trial	CrossFit program effects on physically inactive employees	Sedentary behavior participants (39 in the intervention group and 31 in the control group)	Changes in mobility, strength (maximum isometric strength in kg), well-being (WHO-5 score), and back issues (pain intensity, limitation, and frequency) were assessed before and after 6 months of CrossFit training.	Significant effects were found for mobility and strength, but not for well-being.
Brognara et al. (2023)	Cross-sectional	Stability and postural balance	42 CrossFit athletes	Custom foot orthoses were used for postural/balance assessment. Static and dynamic tests (overhead squats and pistol squats) were performed before and after using different insoles. IMU for postural balance evaluation was used.	In the pistol squat, both orthotic therapies were significantly lower than the average of the oscillations from the first use, with a stable improvement. The overhead squats and pistol squat tests proved a statistically significant benefit.
Butcher et al. (2015b)	Cross-sectional	Relationship between physiological measurements and CrossFit performance	14 CrossFit athletes	Anaerobic power (minimum, average, and peak) in different WODs.	No relationships were found between benchmark WODs (Grace and Fran) and laboratory test variables. The CrossFit Total was the sole predictor of performance in these workouts.
Cejudo (2022)	Cohort study	Optimal upper-limb range of motion for performance	26 CrossFit athletes	Shoulder, elbow, and wrist passive ROM were measured via an inclinometer. Clean technique at 80% 1RM was evaluated initially and after 7 months.	The study found that shoulder external rotation ($\geq 123^\circ$), elbow pronation ($\geq 112^\circ$), and wrist extension ($\geq 90^\circ$) were key for proper clean technique, with a > 85% success rate. Limited ROM increased technical errors and injury risk, highlighting the need for targeted flexibility training in CrossFit.
Cosgrove et al. (2019)	Randomized controlled trial	High-intensity functional training effects	45 participants (men and women) with 0–27 months of high-intensity functional training experience	Participants completed a six-month CrossFit program. Flexibility, power, muscular endurance, and strength were tested before and after the program across three sessions.	All fitness domains improved in women over time, with greater cardiorespiratory gains in the 0–6-month group. In men, flexibility, muscular endurance, and strength showed significant improvements.
Ferreira et al. (2020)	Cross-sectional	Movement efficiency and technical execution	10 trained CrossFit athletes	Joint angles, bar path, concentric phase velocity	Fatigue during deep squats induced significant interquartile variability in biomechanics, with changes in joint coordination and barbell velocity, emphasizing technique degradation under fatigue.

1RM: one-repetition maximum; IMU: Inertial measurement unit; WHO-5 Index: World Health Organization Well-Being Index; WOD: workout of the day

Table 4b. Biomechanical variables of evaluation of CrossFit performance.

Authors	Design	Topic	Sample	Analysis	Main Findings
Haynes and DeBeliso (2019)	Cross-sectional	Relationship between CrossFit performance and handgrip strength	15 female participants of varying experience levels	CrossFit performance was assessed with a WOD of 3 rounds, each consisting of 30 s at four stations: fan bike (max calories), air squats, sit-ups, and burpees (max reps), followed by 2 min and 30 s of rest.	Sit-up performance showed a moderately positive significant relationship with handgrip strength ($r = 0.44$).
Maté-Muñoz et al. (2018)	Cross-sectional	Muscular fatigue responses	32 strength-trained males	Jump height, average power, and maximum take-off velocity during a CMJ (pre- and post-WODs)	The “Cindy” and power clean WODs induced significant losses in jump height (7.3%), take-off velocity (13.8%), relative (4.6%), and average power (4.2%).
Martínez-Gómez et al. (2019)	Cross-sectional	Relationship between strength and power during the full-squat exercise and CrossFit performance	20 trained males	The full squat test used an incremental free-weight protocol, measuring bar velocity with a linear transducer. 1RM was estimated via load-velocity interpolation. Five WODs assessed performance, evaluating 1RM, peak, and mean power.	Squat variables showed moderate to strong correlations ($r = 0.47-0.69$) with WOD performance. Absolute and relative 1RM and relative power were key predictors. Significant group differences were found in strength and power metrics, highlighting their value in assessing CrossFit performance.
Sauvé et al. (2024)	Cross-sectional	Physical profile of elite CrossFit athletes	16 elite CrossFit athletes	1RM strength (squat, bench press, deadlift, clean and jerk), CMJ, SJ, peak power	Elite athletes demonstrated high 1RM values and power output, with CMJ height ~ 44.7 cm and relative back squat 1RM $\sim 2.0 \times$ body mass.
Yüksel et al. (2018)	Randomized controlled trial	Effects of CrossFit on strength	32 trained wrestlers	Cindy was performed 3 times a week for 8 weeks, consisting of AMRAP of 5 pull-ups, 10 push-ups, and 15 air squats in 20 min. An accelerometric system measured squat jump height and bench press force, with the latter assessed using repetitive tests at 30% 1RM.	Cindy’s WOD induced greater improvements than classic wrestling training on squat performance, vertical jump height, bench press force, and bench press bar velocity.
Zeit et al. (2020)	Cross-sectional	Determinants of CrossFit performance	22 recreationally trained individuals	1RM back squat, deadlift, overhead press, and performance on benchmark “Fran” and workout 19.1.	All strength variables showed moderate to strong positive correlations with WOD performance, indicating higher CrossFit performance with greater strength. Fatigue tolerance might influence 19.1 performance due to maximal effort demands. The CrossFit Total workout (maximum strength) was key for optimal performance in time-to-completion tasks with absolute loads.

1RM: one-repetition maximum; AMRAP: as many rounds as possible; CMJ: countermovement jump; WOD: workout of the day

A growing number of studies have explored the biomechanics of key CrossFit exercises, including Olympic lifts like the clean and jerk and snatch, as well as various gymnastic movements (Cejudo, 2022; Martínez-Gómez et al., 2019). These investigations commonly relied on specialized tools to assess performance and movement quality. For example, motion capture systems have been used to analyze joint angles and movement patterns in dynamic tasks (Cejudo, 2022). On the other hand, force platforms have provided insights into ground reaction forces and power output during loaded lifts and jumps (Martínez-Gómez et al., 2019; Maté-Muñoz et al., 2018; Yüksel et al., 2018). Additionally, Ferreira et al. (2020) applied surface EMG and kinematic analysis to examine neuromuscular fatigue and interquartile variability in movement patterns during deep squats in CrossFit athletes, showing that fatigue significantly altered the bar path and joint coordination.

Drawing from these methodologies, we grouped the studies according to their primary objectives: i) experimental interventions incorporating CrossFit training; ii) correlation-based analysis linking biomechanical factors to performance; iii) investigations into the acute responses to different CrossFit training formats; and iv) other biomechanical approaches aimed at understanding movement efficiency and injury risk.

CrossFit as a Training Intervention

Brandt et al. (2022) analyzed the effect of six months of CrossFit training (2 sessions of 60 min per week) in inactive adults. The results showed consistently large positive effects on mobility and strength. The authors concluded that health professionals should consider CrossFit a safe, efficient, and applicable training concept for individuals at risk of developing chronic diseases due to inactivity and sedentary behavior. Cosgrove et al. (2019) examined the effectiveness of a CrossFit program after six months in participants (men and women) with different high-intensity training experiences. That study showed a positive effect of CrossFit program participation on multiple fitness domains, with greater improvements for women with less experience. Yüksel et al. (2018) investigated the effects of CrossFit training on jump and strength variables in healthy men. The experimental group underwent CrossFit training three times a week for eight weeks using Cindy WOD. The findings were consistent with previous research showing the benefits of CrossFit training to physical fitness performance. Studies consistently highlighted the positive effects of CrossFit interventions on fitness performance, mobility, and strength across diverse populations.

Correlational Studies in CrossFit Performance

Haynes and DeBeliso (2019) studied the relationship between CrossFit performance and handgrip strength in women because this variable had been identified as a good predictor of total body strength and ability in CrossFit and non-CrossFit practitioners (DeBeliso et al., 2015). The results only showed a moderately significant relationship between handgrip strength and sit-up performance. The study conducted by Martínez-Gómez et al. (2019) explored the relationship between CrossFit performance and power and strength variables measured in the full-squat exercise. Performance in different WODs was also measured, and overall CrossFit performance was determined. Results showed positive correlations between squat variables and performance in the WODs, with overall CrossFit performance strongly associated with the 1RM and mean and peak power obtained in the full-squat exercise. That study suggested that strength and power variables measured in the full-squat positively related to CrossFit performance, indicating that the squat exercise could predict lower-limb muscle movements in CrossFit. The study by Martínez-Gómez et al. (2019) highlighted the importance of analyzing strength variables in assessing athletic performance, with potential implications for predicting success in CrossFit. Similarly, Sauvé et al. (2024) provided normative data on elite CrossFit male athletes, reporting 1RM back squat values equivalent to ~2 times body mass, CMJ heights of nearly 44 cm, and peak power output exceeding 800 W. Additionally, Zeitz et al. (2020) evaluated the 1RM back squat, the deadlift, and the overhead press, and the sum of the three exercises was determined as the CrossFit Total. Results showed that all strength variables were correlated (moderate to strong) with performance in CrossFit workouts like “19.1” and “modified Fran”, indicating greater CrossFit performance with greater 1RM values. In the same line, Butcher et al. (2015b) analyzed different WODs on separate days and CrossFit Total (1RM back squat, overhead press, and deadlift). Only whole-body strength could partially explain the performance in Grace and Fran WODs, although the anaerobic threshold was also associated with sports performance. Correlational studies highlighted the predictive value of specific strength and power metrics for CrossFit performance.

Acute Effects of CrossFit Training

Maté-Muñoz (2018) assessed the cardiometabolic and muscular fatigue responses to different CrossFit workouts. The workouts resulted in elevated heart rates, the RPE, and blood lactate levels, indicating vigorous exercise intensity. Muscular power losses were observed after the workouts. That study highlighted the importance of quantifying

exercise intensity for proper training load prescription to reduce the risk of injury and optimize performance.

Movement Efficiency and Technical Execution

Cejudo (2022) analyzed the influence of the range of motion of the upper limb's joints on the technical execution and performance of the power clean exercise. That author observed that athletes with a greater range of motion in shoulder external rotation, elbow pronation, and wrist extension were more likely to execute the power clean movement correctly. Building on this, Martínez-Gómez et al. (2019) highlighted the importance of lower-body power by showing a strong association between squat-derived power output and CrossFit performance ($r = 0.47-0.69$) among 20 trained males. Athletes who produced higher peak and mean power output in the full squat tended to perform better in WODs, reinforcing that efficient force production contributed significantly to overall performance. In addition to strength and mobility, control and balance also appeared to be crucial. Brognara et al. (2023) assessed postural stability in CrossFit athletes and found that better balance, especially during demanding tasks such as the overhead squat and the pistol squat, was linked to improved movement control. These insights suggested that minimizing compensatory movements through better postural alignment could enhance technical execution and help prevent injury.

Injury Incidence and Risk Factors

Several studies have investigated injury risk and mechanisms in CrossFit training (Gardiner et al., 2020; Rodríguez et al., 2022), aiming to identify vulnerabilities in specific movements and inform safer training practices. The shoulder (26%), the spine (24%), and the knee (18%) emerged as the most affected regions, likely due to the mechanical demands of overhead lifts, spinal loading, and high-impact plyometrics. The injury incidence in individual studies ranged widely from 12.8% to 73.5%, while reported rates varied between 0.27 and 3.3 per 1,000 training hours. Beyond incidence figures, biomechanical studies offered insights into modifiable risk factors. Cejudo (2022) found that athletes with limited shoulder, elbow, or wrist mobility were more likely to perform the power clean with technical errors, increasing their risk of injury. Similarly, Brognara et al. (2023) demonstrated that postural stability during complex movements like the overhead squat and pistol squat might protect against injury by reducing compensatory patterns. Additionally, Brandt et al. (2022) observed that CrossFit training reduced back

pain in previously sedentary individuals, suggesting that, when properly implemented, CrossFit might also serve as a corrective modality for musculoskeletal discomfort.

These results suggest that CrossFit has a relatively low injury risk and highlight factors like training frequency, duration of CrossFit experience, and the level of competition as important factors in the injury incidence and incidence rates. Finally, researchers have investigated potential performance-enhancing techniques, such as kinematic and kinetic strategies, to optimize training protocols and improve athletic performance in CrossFit. For example, when developing exercise-specific force, the exercise should be completed closer to set failure with fewer repetitions, which can be achieved using complex or high-volume contrast training to pre-fatigue the lighter exercise. When the objective is to improve velocity for the target exercise, it can be combined with a heavier contrast pair to create a post-activation performance-enhancing effect. Alternatively, cluster set designs can be used to maintain high velocities and reduce drop-off, and traditional training is the most effective for increasing the 1RM squat (Marshall et al., 2021; Sauvé et al., 2024).

Physiological Variables

Table 5 shows the most included variables to determine CrossFit's performance, including VO_{2max} , blood lactate concentration, HRV, the RPE, blood and salivary samples, and body composition.

Table 5a. Physiological variables of evaluation of CrossFit performance.

Authors	Design	Topic	Sample	Analysis	Main Findings
Butcher et al. (2015a)	Cross-over	Relative intensity of two types of CrossFit exercise	10 trained CrossFit participants	Heart rate, rating of perceived exertion, session duration, and relative intensity	Both workout formats (circuit and HIIT) elicited high cardiovascular and perceptual responses; HIIT WODs produced higher relative intensity compared to circuit-style WODs.
Butcher et al. (2015b)	Cross-sectional	Relationship between physiological measurements and CrossFit performance	14 CrossFit athletes	VO _{2max} , anaerobic threshold, respiratory compensation threshold, and fatigue index were analyzed during different WODs	Laboratory physiological variables showed no relation to benchmark WODs (Grace and Fran). The CrossFit Total positively correlated with performance in both. Whole-body strength and CrossFit Total explained 77% of the variance in Grace and 42% in Fran, but did not impact Cindy's performance.
Faelli et al. (2020)	Randomized controlled trial	Physiological responses to CrossFit and resistance training	20 moderately trained individuals	Salivary cortisol, interleukin-1 β , and uric acid were assessed via ELISA pre- and post-8-week resistance training to compare with CrossFit training	CrossFit produced a more profound catabolic impact than resistance training.
Fernández-Fernández et al. (2015)	Cross-sectional	Physiological responses to CrossFit workouts.	10 trained subjects	VO ₂ , respiratory exchange ratio, heart rate, blood lactate concentration, and the RPE were measured before and after each WOD	Moderate differences were found in VO ₂ and %VO _{2max} , with higher values in Cindy. Fran had more time above respiratory exchange ratio 1, while Cindy remained below 1. Participants spent 42.2% (Cindy) and 29.3% (Fran) of the workout time above 91% of the maximum heart rate, indicating that training CrossFit 2–3 times/week meets ACSM intensity guidelines for aerobic fitness and fat loss.
Maia et al. (2019)	Case study	Neuromuscular and autonomic responses to a CrossFit competition	3 CrossFit athletes (A, B, and C)	HRV, RPE, CMJ, and internal competition load were evaluated pre- and post-competition	Athlete A showed impaired neuromuscular and autonomic recovery during competition. Athlete C's CMJ declined throughout the first day. Male athletes had reduced HRV, indicating autonomic suppression. Neuromuscular function decreased by the competition's end.

ACSM: American College of Sports Medicine; CMJ: countermovement jump; HIIT: high-intensity interval training; HRV: heart rate variability; VO_{2max}: maximal oxygen uptake; RPE: rate of perceived exertion; WOD: workout of the day

Table 5b. Physiological variables of evaluation of CrossFit performance.

Authors	Design	Topic	Sample	Analysis	Main Findings
Maté-Muñoz et al. (2017)	Cross-sectional	Muscular fatigue responses to three CrossFit modalities: gymnastics, metabolic conditioning, and weightlifting.	34 healthy subjects	CMJ and blood lactate analyzed before and after each CrossFit modality	CMJ performance declined across all CrossFit modalities. Fatigue recovery followed metabolic conditioning, likely due to rest intervals restoring phosphocreatine. High intensity and volume in gymnastics and weightlifting WODs may reduce muscle-tendon stiffness, prolong the CMJ isometric phase, and impair jump ability.
Maté-Muñoz et al. (2018)	Cross-sectional	Cardiometabolic and muscular fatigue responses against different WODs	32 strength-trained males	Heart rate, RPE, and blood lactate were measured before and after each WOD	RPE and the heart rate were significantly higher for Cindy (WOD 1) than the double under (WOD 2) and power clean (WOD 3) workouts. Blood lactate concentration always exceeded 10 mmol/L, indicating a high intensity of exercise.
Sauvé et al. (2024)	Cross-sectional	Physiological profile of elite CrossFit athletes	16 elite CrossFit athletes	VO _{2max} , ventilatory threshold, Wingate test, body composition (DXA)	VO _{2max} ranged from 56 to 64 mL·kg ⁻¹ ·min ⁻¹ ; Wingate peak power exceeded 800 W in males; body fat content was 11.8% in males and 17.2% in females; aerobic and anaerobic capacities were well-developed in elite CrossFitters.
Schlie et al. (2023)	Randomized controlled trial	CrossFit intervention for enhancement of cardiorespiratory fitness and well-being	16 healthy CrossFit beginner athletes	VO _{2max} , WHO-5 Index, body composition, and heart rate reserve pre- and post-intervention	VO _{2max} showed a large improvement, with strong negative correlations between baseline VO _{2max} and its progression after nine months (r = -0.65). Well-being increased by 8.7%, heart rate reserve improved at 1- and 5 minutes post-exercise, and resting metabolic rate rose by 2.2%.
Tibana et al. (2018)	Cross-sectional	Physiological responses to shorter and longer CrossFit training sessions.	9 trained males	Blood lactate, heart rate, and RPE were analyzed during and after a shorter and longer duration CrossFit	Blood lactate concentration was higher after the shorter recovery session (15.9 ± 2.2 mmol/L) compared to the longer session (12.6 ± 2.6 mmol/L; p = 0.019). Blood lactate remained significantly elevated during recovery for both sessions compared to pre-exercise. The RPE increased immediately post-exercise for both sessions, with no significant differences between WODs.
Zeit et al. (2020)	Cross-sectional	Physiological determinants of CrossFit performance	22 recreationally trained individuals	VO _{2max} , ventilatory thresholds, and body composition were analyzed, as well as the performance on the benchmark "Fran" and workout 19.1.	VO _{2max} significantly predicted performance in 19.1 workouts. All strength variables showed moderate to strong positive correlations with CrossFit performance. Fatigue tolerance might also play a key role in 19.1 performance.

CMJ: countermovement jump; VO_{2max}: maximal oxygen uptake; RPE: rate of perceived exertion; WHO-5 Index: World Health Organization Well-Being Index; WOD: workout of the day.

Maximal Oxygen Uptake

Butcher et al. (2015b) analyzed the influence of physiological variables on predicting CrossFit performance in specific WODs. Those authors concluded that CrossFit benchmark WOD performance did not correlate significantly with VO_{2max} , Wingate power/capacity, respiratory compensation, or anaerobic thresholds. Therefore, in addition to their typical training, CrossFit athletes should likely ensure adequate strength and aerobic endurance to optimize performance on at least some benchmark WODs. Schlie et al. (2023) investigated the long-term effects of a CrossFit program in 16 healthy beginner participants. The training program lasted nine months, with two sessions per week. After CrossFit training, significant improvements in VO_{2max} (11.5%) and overall well-being (8.7%) were observed, with a significantly large negative correlation between baseline VO_{2max} and performance improvement ($r = -0.65$), indicating greater adaptations in less conditioned individuals. Therefore, while VO_{2max} continues to serve as a key indicator of aerobic capacity, its role in CrossFit is nuanced, requiring a blend of strength and endurance for optimal results.

Acute Responses to WODs

Butcher et al. (2015a) compared the acute responses to two CrossFit training formats: circuit-based and high-intensity interval workouts. Both elicited vigorous cardiovascular and perceptual responses (e.g., near-maximal HR and RPE values), but the HIIT-style session produced significantly higher relative intensity. Fernández-Fernández et al. (2015) examined the acute physiological effect of two WODs (“Fran” and “Cindy”) in male and female individuals of different performance levels. Both WODs could be characterized as high-intensity workouts, achieving near maximal physiological (e.g., 90–95% of the maximum heart rate) and perceptual responses (e.g., RPE values > 8) in all participants. Tibana et al. (2018) compared the heart rate, blood lactate concentration and the RPE in short- (~4 min) and long-duration (~17 min) CrossFit sessions. Results showed similarities in the maximum heart rate between both protocols, whereas blood lactate concentration was greater in short- compared to long-duration CrossFit sessions. This information could be relevant to determine the type of physiological stress induced in an athlete according to duration and intensity applied during the session, to organize the efforts during a training program. Acute physiological responses highlight the high-intensity nature of CrossFit and the need for careful session structuring to manage stress and fatigue.

Studies conducted by Maté-Muñoz et al. (2017, 2018) analyzed the cardiometabolic and muscular responses to different CrossFit workouts. Those authors found high correlations between blood lactate concentration and the average heart rate in different WODs ($r = 0.92-0.94$). Maia et al. (2019) analyzed internal and external load variables in male CrossFit practitioners during competition. Participants performed five events: bodyweight exercises, Olympic weightlifting, and aerobic activities. The results indicated that two CrossFit competitions on consecutive days negatively influenced the neuromuscular and autonomic function of the male practitioners. Based on these results, trainers and exercise professionals must be cautious when prescribing high-intensity training. Any training with high-intensity exercise, including recovery periods, could be essential to avoid muscle fatigue and decrease the likelihood of injury. In addition, coaches must be sure that individuals assigned to any CrossFit program are free of any cardiovascular or respiratory conditions or injuries that could jeopardize their health.

Competitive Stress and Long-Term Adaptations

Faelli et al. (2020) compared the catabolic and cardiorespiratory responses of CrossFit and resistance training in moderately trained males. Twenty participants were randomly assigned to a CrossFit group ($n = 10$; 30 min/day of WOD) or a resistance training group ($n = 10$; 30 min/day of resistance exercises) for three weeks. Salivary biomarkers, such as cortisol, interleukin- 1β , and uric acid, were significantly elevated in the CrossFit group post-intervention, suggesting a higher acute catabolic effect. Additionally, VO_{2max} and ventilatory thresholds improved significantly in both groups, though the CrossFit group exhibited a slightly greater effect size. No significant changes in body composition were reported for either group across the short intervention period. CrossFit induced greater catabolic responses than resistance training. After prolonged CrossFit engagement, Schlie et al. (2023) highlighted long-term physiological benefits, including VO_{2max} enhancements and improved systemic efficiency. CrossFit's adaptive potential is evident in competitive and recreational contexts, with long-term physical and mental health benefits.

Discussion

This systematic review analyzed the biomechanical and physiological variables related to physical performance in CrossFit. The most frequently evaluated biomechanical variables included movement velocity, force and power output, movement technique, vertical jump performance (e.g., CMJ), and maximum dynamic strength (e.g., 1RM). Considering the physiological aspect, the literature most often assessed VO_{2max} , blood lactate concentration, HRV, and RPE. These measures reflect the dual demands of CrossFit workouts, which blend resistance and metabolic conditioning elements.

Despite the increasing popularity of CrossFit, the number of studies assessing its biomechanical and physiological demands remains limited, particularly among female participants. For example, Schlegel and Křehký (2022) examined sex-based differences in performance at the CrossFit Games, while Mangine et al. (2023) reported that repeated participation in CrossFit-Open workouts led to notable performance improvements, especially among women. Similarly, Kićanović et al. (2022) found that CrossFit training produced greater improvements in body composition than traditional gym-based training in active males, thereby reinforcing CrossFit's utility across diverse populations.

Compared to other modalities, CrossFit appears to elicit physiological adaptations like those seen in high-intensity interval training (HIIT) and traditional resistance programs. Milanović et al. (2015) showed that HIIT significantly improved VO_{2max} , while Schoenfeld et al. (2017) demonstrated the efficacy of heavy-load resistance training in increasing strength and hypertrophy. In CrossFit, the combination or integration of these components offers a hybrid model capable of improving cardiovascular fitness, anaerobic capacity, and body composition across training levels (Gianzina and Kassotaki, 2019; Mangine et al., 2020). Furthermore, due to its time-efficient design, characterized by short rest periods, high power output, and multi-joint movements, CrossFit may offer practical advantages over more time-consuming traditional exercise formats (Claudino et al., 2018; Fernández-Fernández et al., 2015). Notably, high-intensity interval training has also been shown to improve cognitive domains such as inhibitory control and working memory (Yue et al., 2025). Given its structural similarities to HIIT, CrossFit may elicit comparable cognitive benefits, although this hypothesis requires direct testing. Beyond identifying the most studied performance variables, it is critical to interpret what these findings imply for training practices. Movement velocity and power output, for instance, which are strongly correlated with

neuromuscular fatigue, were widely assessed in the reviewed studies (González-Badillo et al., 2022; Sánchez-Medina and González-Badillo, 2011). Prior research has shown that reductions in movement velocity, particularly during resistance training, can serve as reliable proxies for internal fatigue and metabolic stress (Pareja-Blanco et al., 2020; Sánchez-Medina and González-Badillo, 2011). Although this approach has not yet been applied directly in CrossFit, the concept holds promise as a practical, non-invasive method to monitor training intensity and recovery during WODs. From a programming standpoint, velocity-based resistance training could help coaches fine-tune training loads and reduce injury risk due to overreaching, especially during high-volume or high-intensity phases. To advance this line of inquiry, future longitudinal studies should examine the magnitude of velocity loss during different WOD formats, such as “Cindy” and “Fran”, to analyze the degree of neuromuscular fatigue as well as the recovery pattern over time. Additionally, future studies should seek to validate velocity-based fatigue monitoring by comparing it with EMG markers of neuromuscular function during and after CrossFit workouts.

Vertical jump performance, particularly through CMJ testing, also emerged as a standard metric of lower-body power and fatigue. Among the included studies, CMJ performance consistently declined following intense WODs, validating its use as an acute fatigue marker. Its reliability and non-invasive nature make the CMJ a suitable tool for assessing readiness or adjusting training prescriptions in real time. For instance, coaches might delay maximal efforts or reduce volume on days when CMJ performance is compromised. Similarly, 1RM strength testing was prevalent, particularly in Olympic lifts and squats. Findings indicate that CrossFit can yield meaningful strength adaptations, especially among experienced athletes (Bellar et al., 2015). These results are consistent with outcomes seen in traditional resistance training literature (Schoenfeld et al., 2017), affirming the value of incorporating structured strength components within WOD programming. These findings point to the importance of integrating joint mobility, strength, and stability assessments into CrossFit training. Doing so may improve both performance quality and injury resilience during complex, high-load exercises.

From a physiological standpoint, VO_{2max} improvements were well documented across the reviewed studies and consistent with gains seen in HIIT protocols (Milanović et al., 2015). These results support the aerobic efficacy of CrossFit, particularly in novice and recreationally trained populations. Additionally, blood lactate levels and the RPE were consistently elevated post-WOD, indicating high anaerobic and perceptual demands. These responses underline the need for careful recovery planning and suggest that

fatigue management should be a key consideration in WOD sequencing. Meanwhile, HRV data, though limited, pointed to autonomic disturbances following high-intensity efforts, reinforcing the importance of tracking recovery in athletes exposed to frequent WODs. These findings align with observations from Seo et al. (2024), who reported sex-based differences in HRV and vascular function following high-intensity interval training, suggesting that autonomic adaptations may be influenced by sex.

Findings from this review also highlight differences in training adaptations between novice and experienced CrossFit athletes. Individuals with more training experience consistently demonstrated superior aerobic and anaerobic performance (Bellar et al., 2015; Butcher et al., 2015a), and greater familiarity with CrossFit-specific tasks appeared to enhance the training effect (Zeitz et al., 2020). On the other hand, beginners may experience less pronounced improvements initially, potentially due to the high fatigue levels induced by typical WODs. For this population, it may be advisable to implement lower-intensity sessions early on and progressively increase volume and intensity. Coaches are encouraged to support and educate novices through this adaptation phase to ensure long-term adherence and benefits (Schlegel and Křehký, 2022). Future investigations should also consider sex-based differences in physiological and biomechanical responses to CrossFit training. Recent evidence has demonstrated sex-specific physiological adaptations to CrossFit training. For instance, Barreto et al. (2024) reported differential hematological reactions between men and women following 24 weeks of CrossFit, reinforcing the importance of considering sex-based factors when analyzing training adaptations. Stratified analyses by sex may clarify how males and females differ in adaptation patterns, performance output, and injury susceptibility, enabling more precise training recommendations.

It is important to acknowledge the methodological variation across included studies. Experimental designs generally scored highly on the PEDro scale, supporting the reliability of their findings. In contrast, cross-sectional studies varied slightly in methodological quality based on the JBI checklist, particularly in aspects like participants' selection and confounder control. While no studies were excluded due to low quality, these differences might affect the consistency of observed effects and should be considered when interpreting the results. The current review also included diverse populations (trained vs. untrained; males vs. females), study designs (cross-sectional vs. longitudinal), and outcome variables. While this heterogeneity reflects the breadth of CrossFit research, it also limits the direct comparability of findings. For example, strength and endurance outcomes may differ substantially between trained and novice

athletes, and physiological responses can vary by sex. A more stratified analysis of CrossFit's effects, by training level and sex, is needed to provide tailored recommendations and deepen our understanding of its efficacy.

Altogether, these insights highlight the multifactorial nature of performance in CrossFit, where physiological readiness, technical proficiency, and recovery management converge. Future research that incorporates sex-specific analysis, real-time monitoring, and standardized fatigue assessments will be essential for refining CrossFit training strategies. Moreover, the growing availability of wearable technologies presents a promising avenue for monitoring movement quality and fatigue in real time. Future research should investigate the validity of using accelerometers, gyroscopes, and force-sensing devices to detect technique breakdowns, track loading patterns, and optimize feedback during CrossFit workouts.

Limitations

The literature revealed that CrossFit training is important in athletes' physical performance. The present review revealed important information about the variables that may better explain CrossFit training and competition performance. However, it is important to highlight that results of this review present several limitations. First, no meta-analysis was conducted. Due to the considerable heterogeneity in the study design, outcome measures, and participants' characteristics, a meta-analysis was not feasible. Although a narrative synthesis was used to integrate findings, the absence of a formal effect direction summary limits the ability to quantify overall effect trends. Future reviews might explore subgroup analysis or stratified meta-analysis, where data allow for such an approach. Second, the methodological quality of the included studies was assessed using the PEDro scale (for randomized controlled trials) and the JBI checklist (for cross-sectional studies). Although no studies were excluded due to low quality, issues such as small sample sizes, limited use of control groups, and lack of blinding may have affected the internal validity and consistency of results. Third, the studies included in this review encompassed a broad range of participants, including novice and experienced athletes, males and females, and recreational versus competitive populations. This population heterogeneity limits generalizability and makes it difficult to draw specific conclusions applicable to all subgroups. Performance improvements and physiological adaptations were often more pronounced in experienced athletes, suggesting that training status should be more clearly accounted for in future analysis. Finally, female participants were underrepresented in several of the reviewed studies, reflecting a

broader imbalance in CrossFit research. Given the emerging evidence on sex-based differences in training responses and injury patterns (Mangine et al., 2023; Schlegel and Křehký, 2022), this underrepresentation limits the applicability of findings to female athletes. This underrepresentation of female athletes is particularly limiting given emerging evidence of sex-specific adaptations. Barreto et al. (2024), for instance, reported differential hematological responses between men and women after prolonged CrossFit training, underscoring the necessity of sex-stratified research to develop tailored training recommendations. Increasing female inclusion is essential to ensure more inclusive and generalizable insights. Despite these limitations, this review provides a detailed synthesis of current knowledge and identifies key biomechanical and physiological markers relevant to CrossFit performance, monitoring, and programming.

Practical Implications

Understanding the biomechanical and physiological demands of CrossFit is essential for several practical applications across coaching, performance optimization, and injury prevention. Based on the findings of this review, the following implications should be emphasized:

- i) Optimizing athletic performance. Performance-related variables such as the CMJ, the 1RM load, and force or power output were among the most frequently measured in the literature. These key performance metrics can be used to inform individualized resistance training programs. For example, monitoring CMJ performance across resistance training cycles may provide insight into neuromuscular readiness and fatigue status, while monitoring 1RM trends helps assess strength development and program effectiveness.

- ii) Injury prevention and rehabilitation enhancement. Several studies identified the shoulder, the spine, and the knee as the most frequently injured areas in CrossFit athletes (Gardiner et al., 2020; Rodríguez et al., 2022). Cejudo (2022) further demonstrated that a limited range of motion in the upper limbs, particularly in shoulder external rotation and wrist extension, negatively impacted technical execution in movements such as the power clean. Identifying these biomechanical deficits early can aid in correcting movement patterns, reducing injury risk, and supporting safer rehabilitation processes.

- iii) Improved training load management. Physiological markers such as blood lactate concentration and HRV were shown to fluctuate significantly after WODs (Maté-Muñoz et al., 2018; Tibana et al., 2018). These variables provide valuable real-time data on the internal load and recovery needs. Coaches can use these insights to regulate session intensity better, implement recovery strategies, and avoid overtraining, especially in high-volume or competition phases.

- iv) Enhancing coaching strategies and feedback. A deeper understanding of movement velocity, power development, and fatigue progression allows coaches to provide more effective and individualized feedback during training. For instance, using velocity loss as a proxy for neuromuscular fatigue may help coaches adjust work-rest ratios or exercise prescriptions on the spot.

- v) Integration of evaluation and monitoring tools. The use of tools such as the CMJ, movement velocity recording, lactate concentration measurements, and technical movement assessments can be integrated directly into the training environment to monitor progress and adjust programming dynamically. These tools can help coaches and practitioners make evidence-informed decisions and create more responsive training cycles aligned with the athlete's current state.

Conclusions

This systematic review examined the biomechanical and physiological variables most frequently assessed in CrossFit training and competition. Based on the included studies, the following conclusions can be drawn:

- CrossFit training, like other forms of high-intensity training, is associated with improvements in VO_{2max} , muscle strength, hypertrophy, and muscle endurance, while contributing positively to body composition, particularly through reductions in fat mass and increases in lean body mass (Kićanović et al., 2022; Mangine et al., 2023) (Table 5).

- When training volume, relative load, and technical execution are adequately managed, CrossFit can be a safe and effective method of improving fitness in

healthy adults, including recreational practitioners and beginners seeking a diverse and challenging workout routine.

- Biomechanical and physiological variables are commonly used to assess performance and fatigue. The most frequently measured biomechanical markers included movement velocity, force and power output, the CMJ, movement technique, and 1RM strength, as detailed in Table 4. On the physiological side, blood lactate concentration, VO_{2max} , HRV, and RPE were the most reported (Table 5).
- Several studies indicated strong correlations between strength/power indicators (e.g., 1RM, CMJ, velocity loss) and CrossFit performance, particularly in benchmark workouts. In addition, movement technique and postural control, such as range of motion in complex lifts like the power clean, also played a role in performance outcomes, as demonstrated by Cejudo (2022).
- The combined aerobic and anaerobic demands of CrossFit training promote cardiovascular adaptations while simultaneously inducing substantial physiological stress. This aspect was reflected in elevated blood lactate concentration during WODs and in shifts in HRV and RPE scores post-exercise (Maté-Muñoz et al., 2018; Tibana et al., 2018), highlighting the importance of these variables for fatigue monitoring and recovery planning.
- Experienced CrossFit practitioners tend to display greater aerobic capacity, anaerobic power, and training adaptability compared to novices, likely due to greater familiarity with movement standards and competition demands (Mangine et al., 2023; Zeitz et al., 2020). This evidence reinforces the importance of progressive training design for beginners to avoid early fatigue and improve long-term adherence.

Overall, this review reinforces the multidimensional nature of CrossFit, which integrates physiological conditioning with complex movement patterns and variable intensity. These features contribute to improvements in multiple aspects of physical performance, provided the training is structured, individualized, and monitored appropriately.

Chapter 3. Experimental Studies

Study 2. Exploratory Analysis of Correlations Between Physiological and Biomechanical Variables and Performance in the CrossFit Fran Benchmark Workout

Abstract

The multifactorial nature of CrossFit performance remains incompletely understood, particularly regarding sex- and experience-related physiological and biomechanical factors. Fifteen trained athletes (8 males, 7 females) completed assessments of anthropometry, estimated one-repetition maximums (bench press, back squat, deadlift), squat jump (SJ), maximal oxygen uptake (VO₂max), ventilatory responses (VE), and heart rate (HR). Spearman, Pearson, and partial correlations were calculated with Holm and false discovery rate (FDR) corrections. The results showed that males displayed greater body mass, lean and muscle mass, maximal strength, and aerobic capacity than females (all Holm-adjusted $p < 0.01$). Experienced athletes completed Fran faster than beginners despite broadly similar anthropometric and aerobic profiles. In the pooled sample, WOD time showed moderate negative relationships with estimated 1RM back squat ($\rho = -0.54$), deadlift ($\rho = -0.56$), and bench press ($\rho = -0.65$) before correction; none remained significant after Holm/FDR adjustment, and partial correlations controlling for training years were further attenuated. This exploratory study provides preliminary evidence suggesting that maximal strength may contribute to Fran performance, whereas conventional aerobic measures were less influential. However, given the very small sample ($n = 15$, 8 males and 7 females) and the fact that no relationships remained statistically significant after correction for multiple testing, the results must be regarded as preliminary, hypothesis-generating evidence only, requiring confirmation in larger and adequately powered studies.

Keywords: CrossFit, maximal strength, aerobic fitness, training experience, sex differences, exploratory analysis

Introduction

CrossFit is a high-intensity sport that combines weightlifting, gymnastics, and metabolic conditioning, requiring athletes to perform complex movements under fatigue with efficiency and control (Tank & Chung, 2021). Performance is influenced by biomechanical, physiological, and psychological factors, including strength, aerobic capacity, neuromuscular coordination, and mental resilience (Mangine et al., 2020; Meier et al., 2023; Toledo et al., 2021). Athletes with greater muscular fitness and aerobic efficiency generally show superior outcomes, particularly in workouts demanding sustained effort and rapid transitions (Bellar et al., 2015; Magine et al., 2020; Meier et al., 2023). Among these attributes, cardiorespiratory fitness (e.g., $\text{VO}_{2\text{max}}$ and ventilatory thresholds) is associated with quicker recovery between bouts (Dexheimer et al., 2019), while muscular strength enables athletes to lift heavier loads and maintain technical execution under fatigue (Dominski et al., 2020). Optimal CrossFit performance therefore appears to require a combination of physical capacity and psychological readiness (Claudino et al., 2018; Heinrich et al., 2023; Martínez-Gómez et al., 2020; Meyer et al., 2017).

Strength and aerobic capacity have consistently been highlighted as foundational attributes (Behm et al., 2017; Tibana et al., 2021). Strength, particularly maximal values derived from the back squat (BS), deadlift (DL), and bench press (BP), supports Olympic lifting, stability under load, and bodyweight efficiency (Qiu et al., 2016; Meier et al., 2023). Aerobic capacity, typically assessed via $\text{VO}_{2\text{max}}$ and ventilatory thresholds, sustains work output and facilitates recovery in longer-duration workouts (Sánchez et al., 2022; Sauvé et al., 2024; Tibana et al., 2021). These qualities are commonly evaluated through 1RM estimations, jump protocols, and treadmill gas exchange (Benavides-Ubric et al., 2020; Dominski et al., 2020; Lourenço et al., 2011). In recent years, velocity-based methods using the load–velocity (L–V) relationship have provided a valid, efficient, and lower-risk alternative to direct 1RM testing (Anderson & Pandy, 1993; González-Hernández et al., 2020; Sánchez-Medina et al., 2011; Young, 1995). The application of strength, aerobic, and neuromuscular tests in CrossFit research provides a multifaceted physiological and biomechanical profile relevant for monitoring adaptation and predicting performance (Cataldi et al., 2021; Hernández-Belmonte et al., 2023; Martínez-Gómez et al., 2019; Sánchez-Medina et al., 2017; Sánchez-Medina et al., 2011). Yet, the literature does not fully agree on which predictors dominate. Some studies emphasize strength as the key determinant (Qiu et al., 2016), while others highlight aerobic capacity, particularly among female athletes. Mangine et al. (2020) reported that

strength and anaerobic power were most predictive for men, whereas Martínez-Gómez et al. (2020) found aerobic factors to be stronger predictors in women. These findings indicate that sex and training experience may modulate the relative contribution of different physical qualities, but the extent and consistency of these effects remain unclear.

To examine such relationships in an ecologically valid setting, benchmark workouts such as Fran are frequently employed. Performance in Fran, expressed as total completion time, reflects the athlete's ability to integrate force production, movement efficiency, and endurance capacity under high-intensity conditions (Meier et al., 2023). This workout is one of the most widely recognized CrossFit benchmarks, consisting of descending sets of thrusters and pull-ups, and is valued for its simplicity, repeatability, and ability to simultaneously tax strength, aerobic fitness, and coordination (Heinrich et al., 2023; Langford et al., 2023; Feito et al., 2018). Its ecological validity is further reinforced by the standardized load prescriptions and scaling practices that preserve intensity across different fitness levels (Rios et al., 2024; Cruz-Díaz et al., 2020). Although Fran provides a relevant and applied context, it represents only a single CrossFit workout. Previous studies have examined predictors of CrossFit performance, but they have typically addressed isolated domains (e.g., strength or aerobic capacity) or broader batteries of tests, without simultaneously integrating biomechanical, physiological, and anthropometric correlates within the same applied workout (Mangine et al., 2020; Tibana et al., 2021; Qiu et al., 2016; Sanfilippo et al., 2019; Langford et al., 2019). Moreover, few studies have explicitly accounted for sex-related differences and training experience as potential modifiers of these relationships. Given the limited availability of integrated, multifactorial analyses in applied CrossFit settings—and the inherent challenges of recruiting large, homogeneous samples—there remains a gap in understanding how these combined attributes contribute to benchmark performance under ecologically valid conditions.

Therefore, the present investigation was designed as an exploratory, hypothesis-generating study aimed at examining potential biomechanical and physiological correlates of performance in the benchmark workout Fran, with sex treated as a grouping factor and training experience incorporated as a covariate to account for potential confounding. We hypothesized that biomechanical and physiological variables would differ by sex, be affected by expertise, and display relationships with performance outcomes.

Materials and Methods

Study Design

A cross-sectional exploratory design was used to examine potential associations between physiological, neuromuscular, biomechanical variables and specific performance in CrossFit athletes. The primary outcome variable was the time to complete the benchmark WOD “Fran”, while the independent variables included strength, cardiorespiratory, and movement-based variables. Fifteen trained CrossFit athletes (8 males, 7 females) participated in the study and were evaluated at a single time point using a set of standardized laboratory and field-based assessments (Édouard et al., 2017). Training experience (years of CrossFit practice) was recorded as a continuous variable and later used as a covariate in statistical models, rather than as a categorical grouping factor. This approach minimized subgroup instability and maintained statistical power in a small sample.

The study was conducted over six non-consecutive days (with at least 48 h of rest in between sessions), during which participants underwent comprehensive assessments of body composition, strength variables (1RM in BS, DL, and BP, and squat jump evaluation), and cardiorespiratory fitness (VO₂max, heart rate (HR), and resting perceived exertion (RPE)). On day 6, participants completed the WOD “Fran”, a workout consisting of 21-15-9 repetitions of thrusters and pull-ups, performed for time, which served as the primary performance outcome. The experimental protocol was structured into three sequential phases to allow for comprehensive profiling of physiological and biomechanical capacities relevant to high-intensity training (Figure 1). The first phase included baseline assessments, consisting of anthropometrics, body composition analysis, a squat jump test (Benavides-Ubric et al., 2020), and strength testing using incremental 1RM protocols for the BS (Hernández-Belmonte et al., 2023; Sánchez-Medina et al., 2017), BP (Sánchez-Medina et al., 2017), and DL (Benavides-Ubric et al., 2020). The second phase focused on the cardiorespiratory evaluation, which included a treadmill-based test to determine VO₂max, heart rate response (Lourenço et al., 2011), and rating perceived of exertion (RPE) (Borg, 1982). The final phase, on day 6, involved execution of the “Fran” WOD under controlled conditions. During the WOD, internal load was continuously monitored to quantify physiological stress and assess real-world ability capacity. All assessments were performed under standardized and controlled laboratory or field conditions, following established protocols to ensure consistency, reliability, and reproducibility across all measurement domains.

Although 20 athletes volunteered, only 15 completed all phases (8 males: 27.9 ± 5.8 y, 75.2 ± 5.0 kg, 176.5 ± 5.7 cm; 7 females: 27.4 ± 3.1 y, 61.0 ± 4.5 kg, 165.0 ± 3.4 cm). Given the small overall sample and the exploratory nature of the investigation, no priori power analysis was performed; instead, effect sizes and confidence intervals are reported to inform the design of future confirmatory studies.

No a priori sample size calculation was conducted, as this study was explicitly designed as exploratory and hypothesis-generating, based on the convenience sample of trained CrossFit athletes available during the recruitment period. Effect sizes and confidence intervals were therefore prioritized in the analysis to provide preliminary evidence to guide future confirmatory research.

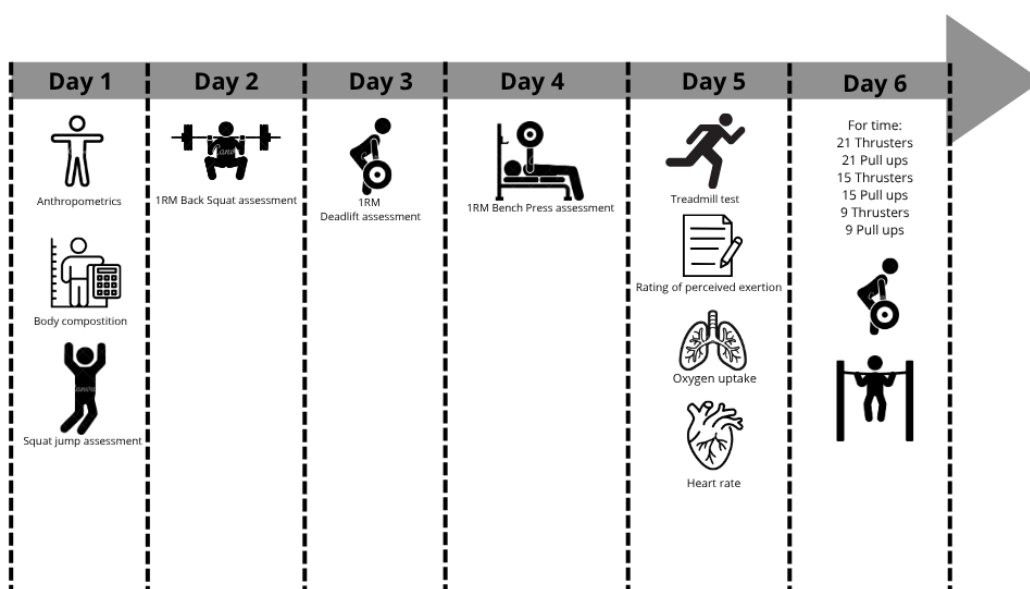


Figure 1. Schematic representation of the experimental protocol.

Sample

A group of 20 trained CrossFit athletes (10 men and 10 women) volunteered to participate in this study. However, two males and three females were absent from at least one testing session (due to illness, injury, or unjustified reasons). Thus, the final sample consisted of 15 participants, comprising 8 males (age: 27.9 ± 5.8 years; body weight: 75.2 ± 5.0 kg; height: 176.5 ± 5.7 cm) and 7 females (age: 27.4 ± 3.1 years; body weight: 61.0 ± 4.5 kg; height: 165.0 ± 3.4 cm). All participants were actively training in CrossFit at the time of data collection, with a minimum of one year of continuous practice and a weekly training frequency of at least three sessions. Training history (years of CrossFit practice)

was recorded for each participant and later used as a continuous covariate in statistical analysis to account for its potential confounding influence, rather than to define discrete subgroups. Weekly training load and competition level are acknowledged as potential confounders. All participants were informed of the study procedures and provided written informed consent. The study was conducted under the Declaration of Helsinki and approved by the institutional ethics committee (CE-UBI-Pj-2024-090-ID2772).

All participants completed a familiarization session one week before testing, including practice trials for the treadmill protocol, L–V testing, and jump assessments. This ensured technical competence and minimized learning effects. Test–retest reliability was established in a subset of participants ($n = 5$), yielding ICC values ranging from 0.88–0.94 for strength measures and 0.86–0.92 for jump variables, consistent with previous reports (Grgic et al., 2020).

Maximum Strength Assessment in the Back Squat, Bench Press, and Deadlift

Recent strength testing research supports the high reliability of load–velocity (L–V) based strength estimation. For example, González-Badillo & Sánchez-Medina (2010), demonstrated a very tight association between mean propulsive velocity (MPV) and %1RM in bench press, which remained stable across sessions. Lawson et al. (2024) reported good to excellent intraclass correlation coefficients (ICC) across velocity measurement devices in exercises such as the back squat and bench press, which supports the methodological decision in this study to use velocity-based estimations and ensure consistency in testing. Prior to each physical test, participants completed a structured warm-up to ensure safety, readiness, and consistent neuromuscular performance. A general warm-up (10 min of light aerobic activity such as cycling or jogging, followed by dynamic mobility drills and muscle activation exercises) was conducted before each test. This was followed by test-specific warm-up routines, described in detail below. Participants received verbal encouragement to ensure maximal effort in all repetitions. All strength tests were conducted using a free-weight Olympic barbell (20 kg, Eleiko, Halmstad, Sweden) and monitored with a Chronojump linear position transducer (Boscosystem, Barcelona, Spain; 3 m cable, 160 Hz sampling rate, 24-bit ADC), which was attached to the bar to record mean concentric velocity. Each test employed a progressive loading protocol, concluding near 80% of the participants' one-repetition maximum (1RM) (Sánchez-Medina et al., 2011). This approach minimized fatigue and injury risk while maintaining ecological validity, estimating the 1RM value.

Back Squat

Back squat performance was assessed using a submaximal, velocity-based loading protocol. A detailed description of the testing procedure used in this study has been reported elsewhere (Hérendez-Belmonte et al., 2023; Sánchez-Medina et al., 2017). For the execution of each repetition, the participants placed the bar on the upper trapezius. In addition, participants were asked to always perform the eccentric phase at a controlled velocity, while the concentric phase was always performed at maximal intended velocity. The specific warm-up included dynamic mobility drills, and 2 sets of 8 and 6 repetitions, respectively, with 20 kg (3-min apart). Following warm-up, testing began at 20 kg for all participants, with progressive increments of 10–20 kg depending on bar velocity, until the movement velocity was less than $0.70 \text{ m}\cdot\text{s}^{-1}$ (~80% 1RM). At each load, participants completed 2–3 repetitions with maximal concentric intent, interspersed with 2–3 min of rest. Only technically valid repetitions performed with full range of motion (i.e., thighs below parallel) were analyzed. The fastest repetition per load, as determined by the highest mean velocity of the propulsive phase (MPV) (Sánchez-Medina et al., 2010), was used for velocity profiling. Estimated 1RM (1RMest) was calculated for each individual from the MPV attained against the heaviest load (kg) lifted in the progressive loading test, as follows: $(100 \times \text{load}) / (25.961 \times \text{MPV}^2) - (50.71 \times \text{MPV}) + 117$ (Sánchez-Medina et al., 2017).

Bench Press

A detailed description of the testing procedure used in this study has been reported elsewhere (Sánchez-Medina et al., 2017). Participants lay supine on a flat bench using a self-selected grip. Specific warm-up consisted of Dynamic shoulder and thoracic mobility drills (e.g., scapular push-ups, shoulder circles), and 2 sets of 8 and 6 repetitions, respectively, with 20 kg (3-min apart). Testing began with 20 kg and progressed in 5–10 kg increments until the movement velocity was less than $0.50 \text{ m}\cdot\text{s}^{-1}$ (~80% 1RM). At each load, participants completed 2–3 repetitions with maximal concentric velocity. Rest intervals were 2–3 min. Proper technique (i.e., feet flat, bar lowered under control to the chest without bounce, and no excessive lumbar extension) was required in each repetition. The fastest technically valid repetition per load was retained for the subsequent analysis. Estimated 1RM was calculated for each individual from the MPV attained against the heaviest load (kg) lifted in the progressive loading test, as follows: $(100 \times \text{load}) / (8.4326 \times \text{MPV}^2) - (73.501 \times \text{MPV}) + 112.33$ (González-Badillo et al., 2010).

Deadlift

Deadlift assessment was based on the protocol by Benavides-Ubric et al. (2020), using a conventional stance and pronated grip. The specific warm-up included: joint mobility (e.g., hip circles, spinal flexion/extension) and 2 sets of 8 and 6 deadlift repetitions with 0.3 kg and 20 kg loads, respectively. The initial load was set at 20 kg for all participants. Then, the progressive loading sequence was structured as follows: (i) 20 kg increments until mean propulsive velocity (MPV) $< 0.80 \text{ m}\cdot\text{s}^{-1}$ (3 reps per load); (ii) 10 kg increments for MPV $0.80\text{--}0.60 \text{ m}\cdot\text{s}^{-1}$ (2 reps per load). Testing concluded when the MPV values corresponded approximately to 80% of the 1RM ($0.58 \text{ m}\cdot\text{s}^{-1}$). Technical validity required a vertical bar path, full hip and knee extension, and no rebending of the knees. The fastest valid repetition per load was used for the subsequent analysis. Rest intervals of 3 min were maintained between sets. Estimated 1RM was calculated for each individual from the MPV attained against the heaviest load (kg) lifted in the progressive loading test, as follows: $(100 \times \text{load}) / (-71.681 \times \text{MPV}) + 121.118$ (Benavides-Ubric et al., 2020).

Squat-Jump Test

In this test, participants began from a stationary semi-squat position on a portable force platform ($42 \times 59 \text{ cm}$, Chronojump Boscosystem, Barcelona, Spain). With knees flexed to approximately 90 degrees, participants performed a maximal vertical jump without countermovement, extending their legs in a single explosive action. Arms remained on the hips throughout, and landing was standardized on the toes to ensure consistency. Performance was assessed based on vertical jump height (cm), which was calculated from flight time using Chronojump's integrated software version v2.2.3 (sampling frequency: 1000 Hz). Each participant performed 3 attempts with 50–60 s recovery time. The highest jump was retained for analysis.

Treadmill Test for Respiratory Gas Exchange and Heart Rate Evaluation

Participants performed a graded treadmill test to assess maximal oxygen uptake ($\text{VO}_{2\text{max}}$) and estimate energy expenditure under standardized conditions. Respiratory gas exchange was measured using a breath-by-breath portable gas analyzer (VO2 Master Health Sensors Inc., Vernon, BC, Canada), and heart rate (HR) was continuously monitored with a chest strap device (Polar S610, Kempele, Finland). The gas analyzer was calibrated for both volume and gas concentrations prior to each session, following

the manufacturer's guidelines to ensure accurate and reliable measurements. The VO₂ Master system, as well as the chest strap device, have been validated in previous research (Feito et al., 2018; Marzano-Felisatti et al., 2024; Batterham et al., 2006), demonstrating strong agreement with criterion laboratory-based systems, making it suitable for field and applied sport science settings. VO_{2max} was determined using standard criteria (achievement of volitional exhaustion plus a plateau in VO₂ despite increasing speed, RER \geq 1.10, or HR \geq 90% age-predicted maximum). Ventilatory thresholds (VT₁, VT₂) were determined using the V-slope method and confirmed by ventilatory equivalents (VE/VO₂, VE/VCO₂) and excess CO₂ criteria. Threshold identification was conducted by two experienced evaluators blinded to the participant subgroup. Inter-rater reliability for VT determination was excellent (ICC = 0.91).

To minimize learning effects, all participants completed a familiarization session one week before data collection, including practice trials for the treadmill, L–V strength assessment, and jump tests. Reliability testing was conducted in a subset of 5 participants, yielding intraclass correlation coefficients (ICCs) between 0.86 and 0.94 across strength and jump measures, consistent with previous reports in similar populations.

After a 3-min warm-up at 8–8.5 km·h⁻¹, the test began at 9 km·h⁻¹ with a fixed incline of 1%. This starting speed was based on performance during prior familiarization sessions. The protocol involved incremental increases in treadmill speed by 0.3 km·h⁻¹ every 25 s, continuing until volitional exhaustion. Participants were verbally encouraged to maintain their effort for as long as possible. VO₂ and HR were recorded breath by breath and averaged over 30-s intervals for analysis, allowing for precise determination of VO_{2max} and mean physiological values throughout the test.

Workout of the Day (WOD)

The benchmark CrossFit workout “Fran” is a widely recognized and frequently used protocol within high-intensity training (HIT), valued for its simplicity and capacity to challenge multiple fitness components such as strength, endurance, and coordination (Feito et al., 2018). Comprising descending sets of 21, 15, and 9 repetitions of thrusters and kipping pull-ups, “Fran” is designed to be completed in the shortest possible time, generating a potent cardiovascular and muscular stimulus. Its structure makes it especially effective for assessing exercise tolerance and overall fitness capacity in training settings (Heinrich et al., 2023). Participants completed Fran according to their

individual training level, using either the Rx or scaled prescription. For correlation analyses, all results were based on athletes' actual completion times. We acknowledge that scaling introduces heterogeneity and may influence comparability; this was considered in the interpretation of the results.

In the present study, participants completed either Rx (as prescribed) version, with a barbell load of 43 kg for males and 29 kg for females, or a scaled version adjusted to individual abilities. Scaled options included lighter loads and pull-up modifications (e.g., band assistance or jumping pull-ups), ensuring inclusivity without compromising the workout's intensity (Cruz-Díaz et al., 2020). This individualized approach aligns with best practices in HIT programming, where scaling is used to preserve safety and ecological validity across varying fitness levels (Dominski et al., 2020). Emphasis on proper execution, such as achieving full squat depth and elbow lockout in thrusters, reflects the importance of standardized performance metrics for both safety and reliable data collection (O'Neal et al., 2016). While "Fran" has also been explored in broader contexts, such as its psychosocial benefits (McLaren et al., 2016), its utility in evaluating physical performance under high-intensity conditions remains clear (Rios et al., 2024).

Rating of Perceived Exertion (RPE)

The RPE was used to assess participants' subjective perception of effort following two key phases of the protocol: the incremental treadmill test and the CrossFit benchmark workout (i.e., Fran WOD). RPE was recorded using the modified Borg CR10 scale, which ranged from 0 (no effort) to 10 (maximum exertion). Participants were instructed on how to interpret and use the scale prior to testing. After completing each effort (treadmill test and Fran WOD), participants were asked to report their overall perceived exertion based on the full-body experience of fatigue, breathlessness, and muscular strain. This measure provided valuable insight into internal load and exertional stress, complementing physiological data such as heart rate and oxygen uptake (Benjamini et al., 1995).

Variables Extracted for Analysis

From each physical and physiological test, a specific set of variables was extracted. For the BS, BP, and DL (performed at approximately 80% of 1RM), the following metrics were recorded: estimated one-repetition maximum (1RM, in kilograms), mean concentric velocity (m/s), mean power output (watts), and mean force output (newtons). In the squat jump (SJ), variables included jump height (cm), calculated from flight time,

take-off velocity (m/s), mean power output (watts), and time of flight (seconds). The cardiorespiratory test provided mean VO_2 and maximal VO_2 (both in $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$), as well as mean heart rate (beats per minute). Anthropometric and body composition assessments yielded body mass (kg), height (cm), lean mass (kg), muscle mass (kg), and fat mass percentage (%). Additionally, age (years) was recorded as a demographic variable. All these variables were included in the correlation analysis with WOD time performance (in seconds), first across the total sample and subsequently stratified by sex (male vs. female) or training experience (beginners vs. experts).

Statistical Analysis

Standard statistical methods were used for descriptive calculations (mean \pm SD or median [IQR] as appropriate). Normality was examined with the Shapiro-Wilk test and homogeneity of variances with Levene's test. Because several variables deviated from normality and the sample was small, non-parametric and estimation-based approaches were prioritized. Sex differences were examined with independent-samples t-tests or Mann-Whitney U tests as appropriate, with effect sizes (Hedges g or Cliff's δ) and 95% confidence intervals (CI) considered the primary outcomes. Associations between Fran performance time and physiological or biomechanical variables were assessed using Pearson and Spearman correlations, and partial correlations controlling for training experience (years) to account for potential confounding. Correlation coefficients (r , ρ) and their magnitude were emphasized, while p -values were reported only descriptively. To limit the risk of Type I error from multiple testing, Holm-Bonferroni and Benjamini-Hochberg false discovery rate (FDR) corrections were applied (Blair, 2007). Both unadjusted and adjusted p -values are provided for transparency, but the results were interpreted primarily in terms of effect size magnitude and precision, consistent with the exploratory purpose of the study. All analyses were performed in IBM SPSS Statistics (Version 23; IBM Corp., Armonk, NY, USA) and JASP (Version 0.18.3.0; JASP Team, Amsterdam, The Netherlands). Statistical significance was interpreted cautiously, emphasizing effect size magnitude and confidence intervals in keeping with the study's exploratory, hypothesis-generating purpose.

Results

Exploratory Analysis of Sex Differences in Anthropometric, Physiological, and Biomechanical Characteristics

Table 1 summarizes the descriptive characteristics of the participants by sex, including mean \pm SD, Hedges g effect sizes, and 95% confidence intervals. Men were taller and heavier and exhibited greater lean and muscle mass compared with women, with large effect sizes (e.g., body mass $g \approx 2.1$, height $g \approx 1.7$, lean mass $g \approx 2.0$). Strength-related variables (estimated 1RM back squat, deadlift, and bench press) likewise showed large sex differences ($g > 1.5$). In contrast, fat mass percentage displayed small and non-meaningful differences ($g \approx -0.5$). Aerobic fitness variables (VO_{2max} and ventilatory thresholds) and neuromuscular power (squat jump height) showed small-to-moderate sex differences, with confidence intervals overlapping zero. Training experience, recorded as years of continuous CrossFit practice, was entered as a covariate and therefore not treated as a grouping factor in these analyses.

Table 1. Sex comparisons are presented with effect sizes and 95% confidence intervals.

Variable	Male Mean \pm SD	Female Mean \pm SD	Hedges g (95% CI)
Age (years)	28.9 \pm 7	27.3 \pm 6	0.24 (-0.78, 1.25)
Body mass (kg)	79.0 \pm 9	62.3 \pm 5	2.13 (0.86, 3.40)
Height (cm)	179 \pm 9	166 \pm 5	1.72 (0.53, 2.91)
Fat Mass (%)	17.7 \pm 5	19.7 \pm 2	-0.49 (-1.52, 0.54)
Lean Mass (kg)	65.0 \pm 8	48.0 \pm 4	2.07 (0.82, 3.33)
Muscle Mass (kg)	33.9 \pm 5	22.1 \pm 2	4.61 (2.67, 6.54)
Years of CrossFit	4.4 \pm 4	3.7 \pm 2	0.19 (-0.83, 1.21)
VO_{2max} [mL/kg/min]	57.4 \pm 7	44.4 \pm 5	2.04 (0.79, 3.30)
1RM Back Squat (kg)	124 \pm 28	84 \pm 13	2.03 (0.80, 3.31)
1RM Deadlift (kg)	151 \pm 28	92 \pm 15	1.97 (0.73, 3.20)
1RM Bench Press (kg)	83 \pm 16	43.2 \pm 7	2.81 (1.38, 4.23)
SJ height (cm)	32.2 \pm 6	26.7 \pm 5	0.95 (-0.12, 2.02)
WOD Time (sec)	374.9 \pm 154	476.1 \pm 190	-0.56 (-1.59, 0.48)

Note: Values are mean \pm SD unless otherwise indicated. Between-sex differences tested using independent-samples t-tests or Mann–Whitney U as appropriate, with effect sizes (Hedges g or Cliff's δ) reported. Holm–Bonferroni adjusted p-values were applied to control for multiple testing. Only strength and anthropometric variables remained statistically significant after correction; no other differences survived.

Mann–Whitney U tests revealed several sex-related differences. However, given the small sample, we emphasize the effect sizes (Hedges g) and their confidence intervals as the most informative outcomes. Large effect sizes were observed for body mass, height,

lean mass, muscle mass, and estimated strength values, while aerobic and neuromuscular variables showed smaller or overlapping effects. These results should therefore be interpreted in terms of magnitude and direction rather than statistical significance alone. Compared with females, males displayed significantly greater body mass ($U = 55.0$; $p = 0.0006$; Hedges $g = 2.13$ [95% CI: 0.86, 3.40]), height ($U = 53.5$; $p = 0.0022$; $g = 1.72$ [0.53, 2.91]), lean mass ($U = 56.0$; $p = 0.0003$; $g = 2.07$ [0.82, 3.33]) and muscle mass ($U = 56.0$; $p = 0.0003$; $g = 2.02$ [0.79, 3.26]). Absolute strength values were also higher in males, with greater estimated 1RM in the back squat ($U = 54.0$; $p = 0.0012$; $g = 1.80$ [0.64, 2.97]), deadlift ($U = 52.0$; $p = 0.0037$; $g = 1.65$ [0.51, 2.78]) and bench press ($U = 56.0$; $p = 0.0003$; $g = 1.95$ [0.76, 3.14]). In addition, males demonstrated moderately higher squat-jump height and VO_{2max} , though effect sizes were smaller and confidence intervals overlapped zero. Training experience (years of CrossFit practice) was entered as a covariate in subsequent analyses and was not used to form subgroups.

Association Between Key Variables and WOD Performance

In Table 2, males presented significantly higher values than females in several key variables. Body mass was 79.0 ± 8.8 kg in males versus 62.3 ± 5.3 kg in females ($U = 55.0$; $p = 0.006$), and height was 179 ± 9 cm versus 166 ± 5 cm ($U = 53.5$; $p = 0.010$). Lean mass and muscle mass were also greater in males (65.0 ± 8.1 kg and 33.9 ± 4.5 kg, respectively) than in females (48.0 ± 4.2 kg and 22.6 ± 2.8 kg; $U = 56.0$; $p = 0.005$ for both). Maximal strength showed similar sex effects: estimated 1RM back squat 124 ± 28 kg vs. 84 ± 13 kg ($U = 54.0$; $p = 0.009$), deadlift 151 ± 28 kg vs. 92 ± 15 kg ($U = 52.0$; $p = 0.015$), and bench press 83 ± 16 kg vs. 43 ± 7 kg ($U = 56.0$; $p = 0.005$). Cardiorespiratory variables also differed, with VO_{2max} 55.1 ± 5.8 vs. 43.2 ± 6.7 mL·kg⁻¹·min⁻¹ ($U = 55.0$; $p = 0.006$), mean VO_2 42.3 ± 6.2 vs. 31.5 ± 5.3 mL·kg⁻¹·min⁻¹ ($U = 53.0$; $p = 0.010$), and maximal minute ventilation (VE_{max}) 157 ± 28 vs. 107 ± 18 L·min⁻¹ ($U = 56.0$; $p = 0.005$). All differences remained significant after Holm correction. No other anthropometric or physiological variables differed significantly, and inclusion of years of CrossFit practice as a covariate did not materially change these findings.

Table 2. Between-sex differences in key anthropometric, strength, and cardiorespiratory variables in trained CrossFit athletes ($n = 15$). Values are presented as mean \pm standard deviation. Group comparisons were performed using the Mann–Whitney U test, with p -values adjusted for multiple testing using the Holm procedure. Only variables showing significant differences or high physiological/biomechanical relevance are reported. VO_{2max} : maximal oxygen uptake; VE_{max} : maximal minute ventilation.

Variables	Males (n = 8)	Female (n = 7)	Mann–Whitney U	p (Holm adj.)
	Mean \pm SD	Mean \pm SD		
Body mass (kg)	79.0 \pm 9	62.3 \pm 5	55.0	0.006
Height (cm)	179 \pm 9	166 \pm 5	53.5	0.010
Lean mass (kg)	65.0 \pm 8	48.0 \pm 4	56.0	0.005
Muscle mass (kg)	33.9 \pm 5	22.6 \pm 3	56.0	0.005
Estimated 1RM Back Squat (kg)	124 \pm 28	84 \pm 13	54.0	0.009
Estimated 1RM Deadlift (kg)	151 \pm 28	92 \pm 15	52.0	0.015
Estimated 1RM Bench Press (kg)	83 \pm 16	43 \pm 7	56.0	0.005
VO_{2max} (mL·kg ⁻¹ ·min ⁻¹)	55.1 \pm 6	43.2 \pm 7	55.0	0.006
Mean VO_2 (mL·kg ⁻¹ ·min ⁻¹)	42.3 \pm 6	31.5 \pm 5	53.0	0.010
Max Ventilation VE_{max} (L·min ⁻¹)	157 \pm 28	107 \pm 18	56.0	0.005

Note: Only variables showing significant differences or high physiological/biomechanical relevance are presented. No other measured variables differed significantly between sexes.

Table 3 shows that WOD completion time was inversely associated with maximal strength variables. Estimated 1RM back squat correlated at $r = -0.57$ ($p = 0.026$), deadlift at $r = -0.55$ ($p = 0.033$), and bench press at $r = -0.61$ ($p = 0.016$). Similar relationships were obtained with Spearman coefficients ($\rho = -0.54$ to -0.65). Fat mass and age displayed weaker, non-significant correlations ($r \approx -0.24$ to 0.28 ; $p > 0.30$). Partial correlations adjusted for years of CrossFit practice remained negative for the main strength variables ($r \approx -0.30$ to -0.40) but did not reach significance. After applying Holm and false discovery rate (FDR) corrections for multiple testing, no correlation remained statistically significant.

Table 3. Bivariate and partial correlations between Fran workout completion time and key anthropometric, strength, and body-composition variables in trained CrossFit athletes ($n = 15$). Values are Pearson's correlation coefficient (r) and Spearman's rank correlation coefficient (ρ) with corresponding p -values; partial r represents Pearson correlations adjusted for years of CrossFit practice. Holm and false discovery rate (FDR) procedures were applied to adjust for multiple comparisons. Negative coefficients indicate that higher values of the predictor variable are associated with faster completion times (better performance).

Variable	Pearson r (p)	Spearman ρ (p)	Partial r adj.		
			Years of CF (p)	p Holm adj	p FDR adj
Age	-0.24 (0.394)	-0.19 (0.502)	0.26 (0.342)	0.394	0.394
Fat Mass (%)	0.28 (0.315)	0.23 (0.403)	0.21 (0.462)	0.946	0.349
Estimated 1RM Back Squat (kg)	-0.57 (0.026)	-0.54 (0.039)	-0.39 (0.155)	0.318	0.111
Estimated 1RM Deadlift (kg)	-0.55 (0.033)	-0.56 (0.028)	-0.30 (0.284)	0.359	0.111
Estimated 1RM Bench Press	-0.61 (0.016)	-0.65 (0.009)	-0.40 (0.137)	0.225	0.111

Note: Pearson, Spearman, and partial correlations between Fran completion time and selected variables. Reported values are correlation coefficients with corresponding p -values in parentheses. Holm and FDR adjusted p -values account for multiple testing. Although some raw p -values were < 0.05 , no relationships remained statistically significant after correction.

Following the correlation analysis summarized in Table 3, maximal strength variables showed moderate inverse relationships with WOD completion time (Pearson r ranging from -0.55 to -0.61 ; Spearman $\rho \approx -0.54$ to -0.65). Fat mass and age displayed weak and non-meaningful relationships ($r \approx -0.24$ to 0.28), and all other variables were trivial in magnitude. Partial correlations adjusted for years of CrossFit experience remained negative for the main strength measures ($r \approx -0.30$ to -0.40), though of smaller magnitude. Partial correlations adjusted for years of CrossFit experience remained negative for the main strength measures ($r \approx -0.30$ to -0.40), though smaller in magnitude. However, these analyses were clearly underpowered given the small sample size and therefore should be regarded as descriptive and exploratory only. These relationships were moderate in effect size but did not remain statistically significant after correction for multiple testing (Holm or FDR). Accordingly, the results should be interpreted in terms of the magnitude and direction of associations rather than statistical significance alone, reinforcing their exploratory and hypothesis-generating nature.

Figure 2 provides a visual representation of these relationships, highlighting stronger negative relationships between WOD completion time and maximal strength variables for Spearman correlation test. However, it is important to note that this should be analyzed with caution due to the loss of significance in Holm and FDR corrections.

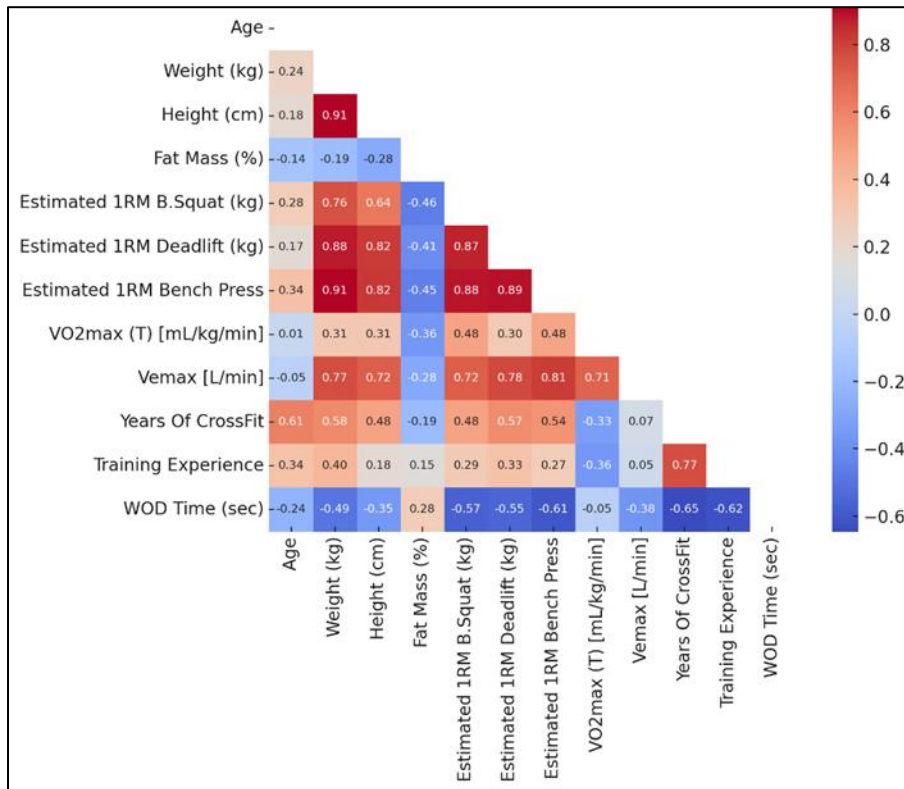


Figure 2. Pearson correlation heatmap among anthropometric, strength, aerobic, experience, and performance variables ($n = 15$). Stronger negative values (blue) indicate faster Fran completion times, whereas positive values (red) reflect slower performance. Only the lower triangle is shown for clarity. Although several raw correlations with WOD time appeared moderate in magnitude, none remained statistically significant after Holm–Bonferroni or FDR correction for multiple testing.

Discussion

This study aimed to explore physiological and biomechanical correlates of performance in the benchmark CrossFit workout Fran, with attention to potential sex- and experience-related effects. We hypothesized that (i) male athletes would display superior strength, jump performance, and aerobic capacity, (ii) more experienced athletes would complete the WOD faster, and (iii) these physiological characteristics would correlate with performance in a subgroup-specific manner. The findings partly supported these hypotheses; however, it is important to note that all analyses must be interpreted as exploratory and hypothesis-generating due to the small sample size and the loss of statistical significance after correction for multiple testing.

Consistent with established literature on neuromuscular and morphological dimorphism (Hunter et al., 2023; Senefeld et al., 2024; Zhang et al., 2025; Hodžić et al., 2023), males demonstrated significantly higher body mass (79.0 ± 8.8 kg vs. 62.3 ± 5.3 kg), stature (179 ± 9 cm vs. 166 ± 5 cm), lean mass (65.0 ± 8.1 kg vs. 48.0 ± 4.2 kg), and muscle mass (33.9 ± 4.5 kg vs. 22.6 ± 2.8 kg) compared with females. They also outperformed females in estimated one-repetition maximum (1RM) for the back squat, deadlift, and bench press (all $p < 0.01$ after Holm correction), and in cardiorespiratory variables such as $\text{VO}_{2\text{max}}$ (55.1 ± 5.8 vs. 43.2 ± 6.7 mL·kg⁻¹·min⁻¹) and maximal minute ventilation (VE_{max} : 157 ± 28 vs. 107 ± 18 L·min⁻¹). These sex-specific differences align with previous work in fitness and strength sports (Dominski et al., 2020; Butcher et al., 2015). Nevertheless, the small subgroups ($n = 8$ and $n = 7$) yield wide confidence intervals and prevent confirmatory inference.

Athletes with ≥ 4 years of CrossFit practice completed Fran faster than those with less experience, supporting the relevance of accumulated training history, technical proficiency, and pacing strategies described in earlier reports (Claudino et al., 2018; Sauv e et al., 2024). However, once year of CrossFit experience was treated as a covariate instead of a grouping factor, no additional physiological predictors emerged. This finding reinforces the idea that practice-related adaptations, skill acquisition, movement economy, and tactical execution may mediate performance more than isolated physiological traits (Mangine et al., 2020; Tibana et al., 2021).

Correlation analyses across the total sample revealed moderate negative relationships between WOD completion time and maximal strength variables – estimated 1RM back squat ($r = -0.57$, $p = 0.026$), deadlift ($r = -0.55$, $p = 0.033$), and bench press ($r = -0.61$, $p = 0.016$)—with similar Spearman coefficients ($\rho = -0.54$ to -0.65). These relationships are in line with previous findings identifying maximal strength as a primary determinant of fitness performance (Meier et al., 2023; Qiu et al., 2016; Langford et al., 2023; Cohen, 1988). Fat mass and age showed only weak, non-significant correlations. Crucially, none of these associations survived Holm or FDR correction, reinforcing their preliminary and descriptive character. Partial correlations controlling training experience were smaller in magnitude and underpowered and therefore should be interpreted as exploratory only.

Within these constraints, the present findings generate hypotheses for programming. They tentatively suggest that maximal strength in fundamental lifts (back squat, deadlift,

bench press) may contribute meaningfully to benchmark WOD performance, whereas traditional cardiorespiratory markers such as VO_{2max} may play a lesser role in this specific workout. However, the current evidence is inconclusive, and no practical prescriptions can be drawn from these results. Instead, these exploratory observations highlight the need for replication in larger, adequately powered studies that incorporate multiple benchmark workouts, competition-level contexts, and broader assessments, including psychological, technical, and tactical determinants of performance.

Limitations

Several limitations must be underscored. First, the sample size was very small ($n = 15$; 8 males and 7 females). This severely restricts statistical power, increases the risk of spurious or inflated correlations, and explains why none of the initially significant relationships survived multiple-comparison correction. As a result, the present findings must be interpreted strictly as preliminary, hypothesis-generating evidence rather than confirmatory outcomes (O'Neal et al., 2016; Cohen, 1988; Lakens, 2013).

In addition, the partial correlation analyses that controlled training experience were not adequately powered, given the small sample size. Although they provided useful exploratory insights, these results should be interpreted with extreme caution and cannot be generalized. Larger samples are required to properly evaluate the independent contribution of training experience to performance outcomes. Multiple comparisons further heighten the risk of Type I error, and even with effect-size reporting, our findings remain preliminary. The analysis was restricted to a single WOD (Fran), limiting generalizability to other CrossFit workouts with different physiological demands (Toledo et al., 2021; Cruz-Díaz et al., 2020).

Another limitation is the ecological scope of the design. While Fran is a widely recognized CrossFit benchmark, it represents only a single workout format. As such, the present findings may not generalize to other CrossFit workouts with different physiological or technical demands, nor to formal competition contexts where pacing strategies, judging standards, and psychological stressors also influence performance. Additionally, although both Rx and scaled versions of Fran were accepted to preserve ecological validity and inclusivity, this introduces heterogeneity that may confound direct comparisons.

Psychological, technical, and cognitive determinants of performance-known contributors to success in CrossFit, were not assessed (Meyer et al., 2017; Lakens, 2013). Finally, although VO_{2max} was determined using established criteria (volitional exhaustion with VO_2 plateau, $RER \geq 1.10$, or $HR \geq 90\%$ of predicted maximum), not all participants may have fulfilled every criterion simultaneously, so these values are best interpreted as reflecting near-maximal aerobic capacity.

In summary, this study suggested that maximal strength in fundamental lifts could possibly explain the performance in the CrossFit Fran workout, whereas conventional aerobic measures appear less influential. However, these findings are inconclusive and should only be viewed as exploratory, requiring replication in larger, longitudinal cohorts that incorporate multiple WODs, formal competition-level classification, and broader assessments of physiological and technical determinants of performance.

Practical Applications

Despite these limitations, preliminary trends suggest that maximal strength in fundamental lifts (back squat, deadlift, bench press) may contribute more to Fran performance than conventional aerobic markers. For practitioners, this implies that monitoring and developing strength qualities remains relevant for performance in short, high-intensity CrossFit benchmarks. In practical terms, coaches may consider systematically tracking athletes' strength alongside conditioning variables to better understand their readiness and performance potential. However, these insights must be interpreted with caution and should not yet be used to prescribe training strategies; they remain exploratory hypotheses that require confirmation in larger, adequately powered studies incorporating multiple workouts and broader performance determinants.

Conclusions

This study provided exploratory, hypothesis-generating results suggesting that males displayed higher values in anthropometric, biomechanical, and physiological parameters compared with females. Maximal strength variables, particularly the back squat, deadlift, and bench press, showed moderate negative relationships with performance in the benchmark CrossFit workout Fran, whereas conventional aerobic markers (e.g., VO_{2max} , ventilatory indices) appeared less influential in this specific task. However, given the very small sample ($n = 15$) and the fact that none of these relationships remained statistically significant after correction for multiple testing, the findings should

be regarded as preliminary and inconclusive. Future research with larger and adequately powered cohorts, multiple benchmark workouts, and broader assessment of psychological and technical determinants is required to confirm or refute these exploratory observations.

Study 3. Exploratory Analysis of Physiological and Biomechanical Determinants of CrossFit Benchmark Workout Performance: The Role of Sex and Training Experience

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 beginners 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.

Keywords: CrossFit, WOD, physiology, biomechanics, performance, experience, sex

Introduction

CrossFit is a form of high-intensity training that combines gymnastics, Olympic weightlifting, and metabolic conditioning into varied, time- or task-based workouts known as “Workouts of the Day” (WODs) (Mangine et al., 2020; Jacob et al., 2020). 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 (Dexheimer et al., 2019; Camacho-Cardenosa et al., 2020; DeBlauw et al., 2021). 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 (Forte et al., 2022; Toledo et al., 2021). 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 (Fernández et al., 2015). Notably, Cindy produced higher oxygen uptake, relative VO_{2max} , and energy expenditure compared with Fran. Beyond acute responses, predictors of performance have also been investigated. Leitão et al. (2021) 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) (Zeitz et al., 2020). At the same time, longitudinal interventions indicate chronic adaptations such as increased testosterone, reduced cortisol, and altered CD8 lymphocyte levels (Sanfilippo et al., 2019). Importantly, sex-based differences have also emerged. Rios et al. (2025) 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 (Zeitz et al., 2020; Rios et al., 2024; Senefeld et al., 2024; Archacki et al., 2024; Tucker et al., 2019; Qiu et al., 2016; Woo et al., 2006; Weiss et al., 2006), many studies have not accounted for individual-level moderators such as biological sex or training experience (Rodrigues et al., 2023). Sex-based differences in body composition (Schlegel et al., 2022; Micklewright et al., 2010), oxygen kinetics (Weiss et al., 2006; Myer et al., 2006), hormonal responses (Sanfilippo et al., 2019; Ferraz et al., 2025; Lambrick et al., 2013), and ventilatory thresholds (Menting et al., 2022; Fiorenza et al., 2019; Bellar et al., 2015; Meier et al., 2023) are known to influence performance, with recent evidence showing that men generally complete benchmark workouts faster and exhibit higher peak cardiorespiratory responses than women (Rios et al., 2025; Claudino et al., 2018; Mangine et al., 2022; Aravena-Sagardia et al., 2025; Schisterman et al., 2009). Training experience also affects biomechanical efficiency (Szklo et al., 2014; Howards et al., 2018; Lindmark et al., 2018), pacing strategies (Becher et al., 1992; Zhao et al., 2020), and metabolic efficiency (Forte et al., 2025; Higgins et al., 2018), all of which may moderate fatigue and performance outcomes (Weiss et al., 2006; Bagchi et al., 2024). Failing to consider these moderators risks biased or incomplete interpretations of performance data (Senefeld et al., 2024; Weiss et al., 2006; Sands et al., 2020), thereby limiting the external validity of monitoring strategies across athlete subgroups (Woo et al., 2006; Panoutsakopoulos et al., 2021; Edwards et al., 2023), especially in the context of CrossFit. To date, only a limited number of studies have compared athletes' performance based on training experience in CrossFit (Langford et al., 2023; Breitbach 2014; Coco et al., 2021). 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 (Rios et al., 2025; Claudino et al., 2018; Mangine et al., 2022; Aravena-Sagardia et al., 2025; Schisterman et al., 2009). Nonetheless, these moderators are still often overlooked and may act as confounding factors (Piero et al., 2018; Hunter et al., 2023) and lead to biased or misleading interpretations of performance outcomes (Sandbakk et al., 2022). Given the multifactorial and individualized nature of athletic performance (Bellar et al., 2015; Meier et al., 2023), 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 (Piero et al., 2018; Hunter et al., 2023; Sandbakk et al., 2022).

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 (VE) 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.

Materials and methods

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 (Panoutsakopoulos et al., 2021), 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 (Fernández et al., 2015; Leitão et al., 2021; Rios et al., 2025; Claudino et al., 2018), 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.

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 (Hung et al., 2025). 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 (Forte et al., 2022; Toledo et al., 2021; Cormie et al., 2011). Furthermore, the use of HRV as a non-invasive marker of training load and recovery has been supported in prior high-intensity training studies (DeBlauw et al., 2021).

Squat Jump (SJ) and Countermovement Jump (CMJ)

Neuromuscular performance was evaluated using a portable force platform (42×59 cm, Chronojump Biosystem, 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 (Camacho-Cardenosa et al., 2020). This instrument validity was previously reported in the literature (Dominski et al., 2021; McLaren et al., 2016).

For the squat jump (SJ), participants began from a stationary semi-squat position with knees flexed to $\sim 90^\circ$, maintaining hands on the hips throughout (Figure 1, left picture). From this static position, they performed a maximal vertical jump without countermovement, extending their 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 (Kaufman et al., 2023). 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 ($W \cdot kg^{-1}$) from this trial were retained for analysis, as suggested in the literature (Schlegel et al., 2022; Pueo et al., 2020). Both tests were performed before and immediately after the WOD to quantify fatigue-induced changes in neuromuscular function.

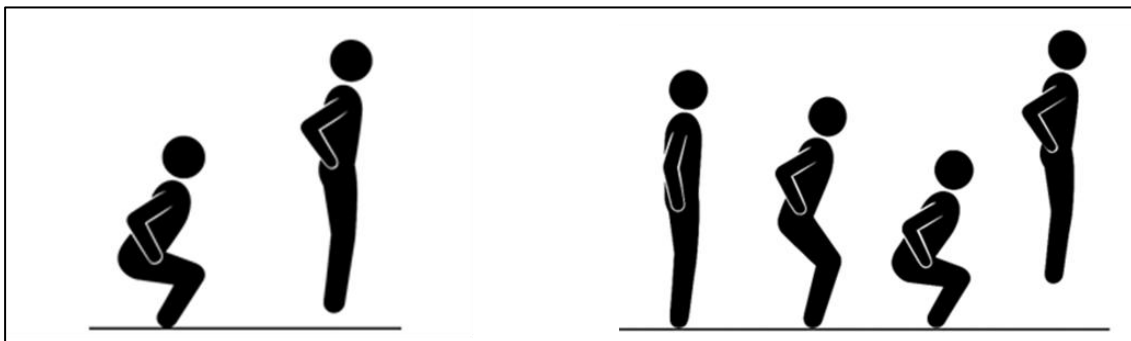


Figure 1. Standardized execution of squat jump (left) and countermovement jump (right) tests.

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 training (HIT) research and its ability to integrate strength and metabolic conditioning in a simple yet demanding format (Weiss et al., 2006). Fran consists of descending sets of 21, 15, and 9 repetitions of thrusters and kipping pull-ups, performed for time (Cesanelli et al., 2022). The prescribed (Rx) version uses a barbell load of 43 kg for males and 29 kg for females (Feito et al., 2018). 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 (Myer et al., 2006). 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 (Blair et al., 2007). WOD completion time (s) were recorded as the primary measure of 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 (Rios et al., 2024; Feito et al., 2018). 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).

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 ($\approx 50\text{--}60\%$ of HR_{\max}), 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 (Cruz-Díaz et al., 2020; D’Hulst et al., 2024).

During the WOD, respiratory gas exchange was measured breath-by-breath using a portable gas analyzer (VO₂ 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 VO₂ Master system and the chest strap device have been validated in previous research (Cruz-Díaz et al., 2020; D’Hulst et al., 2024), 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.

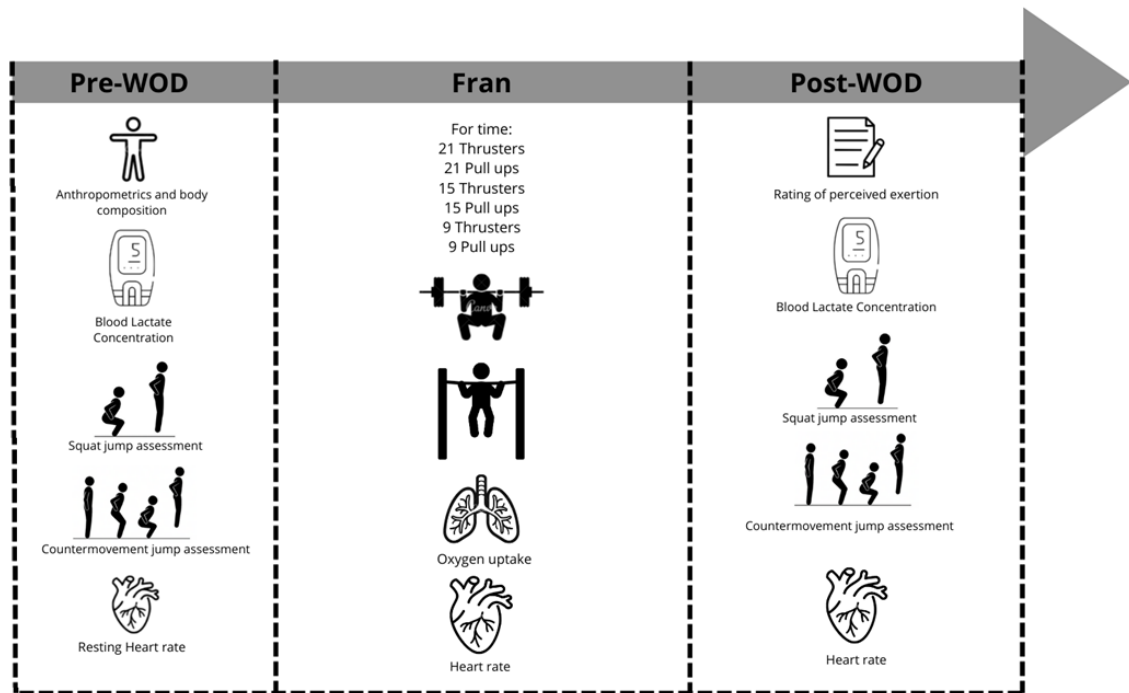


Figure 2. Schematic representation of the experimental protocol. Assessments were conducted pre-WOD (anthropometrics, body composition, blood lactate concentration, squat and countermovement jump performance, resting heart rate), during the benchmark CrossFit workout Fran (respiratory gas exchange, heart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

Blood Lactate

Capillary blood lactate concentration ($\text{mmol}\cdot\text{L}^{-1}$) was measured immediately before and after the WOD to evaluate metabolic response. For the pre-exercise measure, a sample ($\sim 5\ \mu\text{L}$) was collected from the earlobe following a period of seated rest to ensure a stable baseline (Díaz et al., 2019). 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, Arkay Inc., Kyoto, Japan), which was calibrated before each testing session according to manufacturer guidelines (Fernández et al., 2015). The earlobe was disinfected before each puncture, and sterile, single-use lancets were employed to maintain hygienic standards (Fernández et al., 2015; Édouard et al., 2017). All assessments were performed according to standardized protocols (Fernández et al., 2015), with equipment calibrated before testing and procedures delivered by the same experienced assessors to ensure reliability and reproducibility (Édouard et al., 2017).

Statistical Analysis

Data were first screened for normality using the Shapiro–Wilk test. Continuous variables are presented as mean \pm 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 ($d \geq 0.80$) (Ferraz et al., 2025). The associations between baseline physiological and neuromuscular predictors (e.g., VO₂max, 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 ($\rho < 0.30$), moderate ($\rho = 0.30–0.49$), and strong ($\rho \geq 0.50$) (Cohen, 1988). 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., Δ HR, Δ VO₂, Δ Ve, Δ CMJ, Δ SJ, 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)

Results

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 (Δ SJ height: -2.77 ± 3.28 cm; Δ SJ power: -43.3 ± 52.8 W) and countermovement jump (Δ CMJ height: -4.09 ± 3.23 cm; Δ CMJ power: -69.2 ± 61.9 W). The physiological responses reflected high metabolic and cardiovascular stress, with large post-exercise increases in blood lactate (Δ Lactate: $+12.3 \pm 1.6$ mmol·L⁻¹), oxygen uptake (Δ VO₂: $+26.9 \pm 5.5$ mL·kg⁻¹·min⁻¹), heart rate (Δ HR: $+69.8 \pm 16.1$ bpm), and ventilation (Δ Ve: $+91.9 \pm 21.6$ L·min⁻¹). Minimum HRV during the WOD showed a marked decline (Δ HRV: $+40.3 \pm 19.5$ ms).

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

	WOD Time (s)	Δ SJ (cm)	Δ SJ (W)	Δ Lactate [mmol/L]	Δ VO ₂ [mL/kg/min]	Δ HR (bpm)	Δ Ve [L/min]	Δ HRV [ms]	Δ CMJ (W)	Δ CMJ (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

WOD: workout of the day; SJ: squat jump; CMJ: countermovement jump; HR: heart rate; VO₂ : oxygen consumption; VE: ventilatory response; HRV: heart rate variability.

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 (Δ CMJ: -4.0 ± 3.2 cm vs. -4.2 ± 2.9 cm; $p = 0.92$, $d = 0.05$, small effect) or squat jump height (Δ SJ: -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 (Δ Lactate: 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.

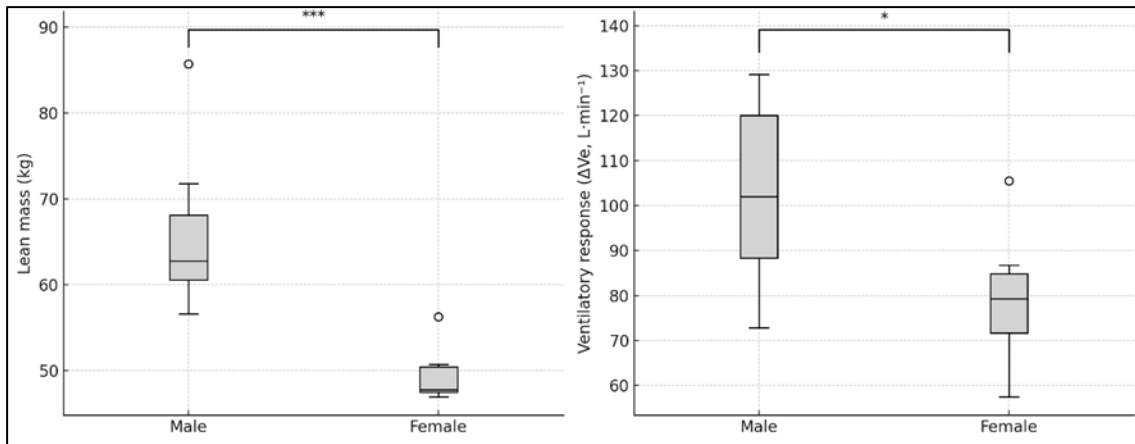


Figure 3. Boxplots (median, interquartile range, minimum–maximum, and outliers) of lean mass (kg) and ventilatory response (ΔV_e , $L \cdot \text{min}^{-1}$) stratified by sex. Asterisks indicate significant differences (* $p < 0.05$; *** $p < 0.001$).

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 $\text{mmol} \cdot \text{L}^{-1}$ vs. 11.7 ± 2.8 $\text{mmol} \cdot \text{L}^{-1}$; $p = 0.22$, $d = 0.71$, 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.

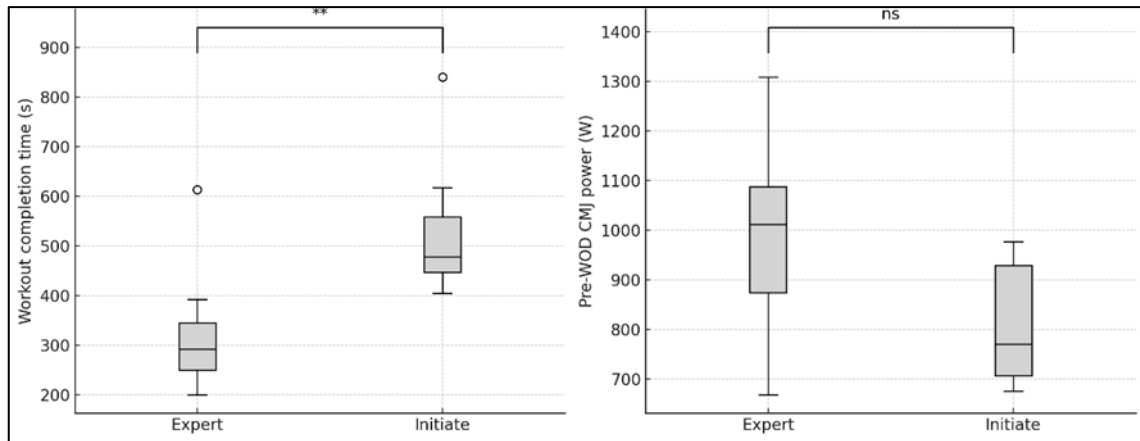


Figure 4. Boxplots (median, interquartile range, minimum–maximum, and outliers) of (A) workout completion time (s) and (B) pre-WOD countermovement jump (CMJ) power (W), stratified by expertise level. Asterisks indicate significant differences (** $p < 0.01$; ns = non-significant).

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 ($\rho = -0.46, p < 0.05^*$) and larger ventilatory responses (ΔV_e) ($r = -0.65, p < 0.01^{**}$). 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.

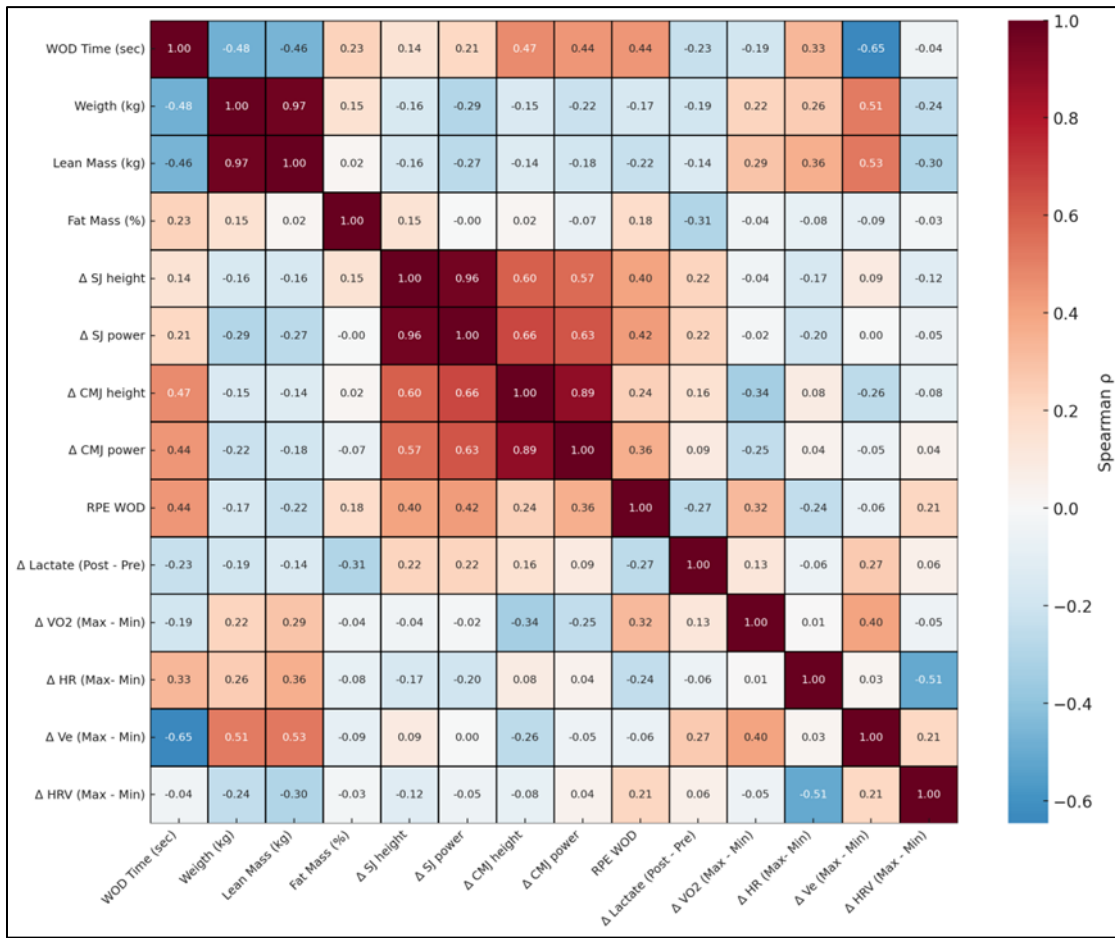


Figure 5. Spearman’s rank correlation coefficients (ρ) between physiological, biomechanical, and perceptual variables and workout completion time (WOD Time, s) for the total sample ($n = 15$). Color scale indicates direction and magnitude of correlations (blue = negative, red = positive). Numeric values 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 VO₂, 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 Δ Ve ($r = -0.76, p < 0.05^*$). 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 ($r = 0.81, p < 0.05^*$).

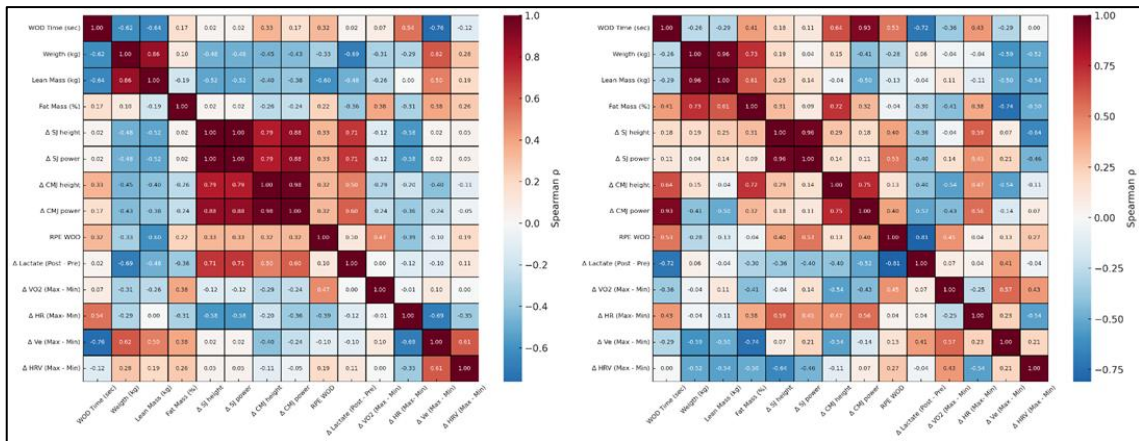


Figure 6. Spearman's rank correlation coefficients (ρ) between physiological, biomechanical, and perceptual variables and workout completion time (WOD Time, sec), stratified by sex (Male: $n = 8$, left panel; Female: $n = 7$, right panel). Color scale indicates direction and magnitude of correlations (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 ($r = 0.59, p = 0.046$).

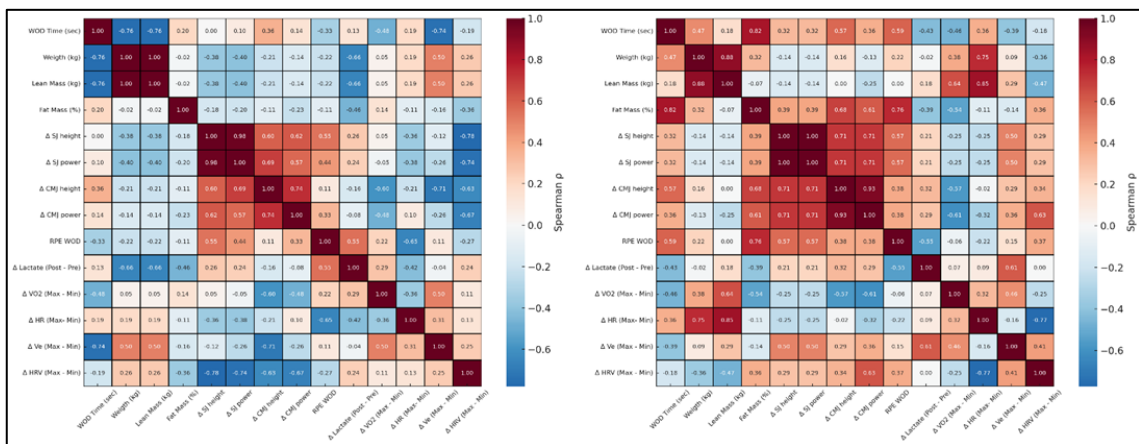


Figure 7. Spearman's rank correlation coefficients (ρ) between physiological, biomechanical, and perceptual variables and workout completion time (WOD Time, sec), stratified by training experience (Expert: $n = 7$, left panel; Initiate: $n = 8$, right panel). Color scale indicates direction and magnitude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

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.

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 (DeBlauw et al., 2021; Schlegel et al., 2022; Martínez-Gómez et al., 2019). 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 (Schlegel et al., 2022). Ventilatory responses (ΔV_e) were also significantly associated with faster completion times, corroborating findings from (Dexheimer et al., 2019; D'Hulst et al., 2024), 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 (ΔV_e) 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 training (Edwards et al., 2023; Martínez-Gómez et al., 2020). 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 (Schlegel et al., 2022; Martínez-Gómez et al., 2019). 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 (Leitão et al., 2021). 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 (D’Hulst et al., 2024; Koznic et al., 2021).

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 (Weiss et al., 2006; Myer et al., 2006; Edwards et al., 2023; Martínez-Gómez et al., 2019). 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 (Schlegel et al., 2022; Micklewright et al., 2010), which increase the relative intensity of each repetition and accentuate neuromuscular fatigue and perceptual strain during benchmark workouts (D’Hulst et al., 2024; Martínez-Gómez et al., 2020). 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 (Senefeld et al., 2024; Marzano-Felisatti et al., 2024). More experienced athletes also tend to present greater muscle mass and superior neuromuscular efficiency, which enhances their ability

to sustain explosive power under fatigue (Marzano-Felisatti et al., 2024). 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 (Tucker et al., 2019; Micklewright et al., 2010; Bagchi et al., 2024). 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 (Panoutsakopoulos et al., 2021).

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 (Maté-Muñoz et al., 2025), focusing on fatigue management (Petrigna et al., 2019), body composition optimization (Ponce-García et al., 2024), and pacing strategies in beginners and female athletes (Fernández et al., 2015; Ponce-García et al., 2025), while emphasizing ventilatory conditioning (Rios et al., 2025) and neuromuscular power in advanced and male athletes (Tibana et al., 2021). 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 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 (Senefeld et al., 2024; Sands et al., 2020; González-Badillo et al., 2011). (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

spacing practice during mixed-modal sessions (Martínez-Gómez et al., 2020; Pryor et al., 2020). 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 (Tucket et al., 2019; Ponce-García et al., 2025). (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 (Panoutsakopoulos et al., 2021) Sauv e et al., 2024).

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 (Rios et al., 2024), 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 (Butcher et al., 2015). Fourth, contextual factors such as nutrition, sleep, and recovery status were not directly controlled, which may have influenced both physiological responses and performance outcomes (Ponce-García et al., 2025; Zhang et al., 2025). 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 (Zeitz et al., 2020; González-Badillo et al., 2011; Smajla et al., 2024), 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.

Conclusion

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.

Chapter 4. General Discussion

The general purpose of the current doctoral thesis was to analyze the physiological and biomechanical determinants of CrossFit performance, and to examine how individual factors such as sex and training experience moderate the contribution of these variables. To address this purpose, a sequence of three studies was conducted with the following specific aims:

- i) To systematically review the evidence on the physiological and biomechanical demands of CrossFit and their relation to performance;
- ii) To experimentally investigate the main physiological and biomechanical predictors of performance in a benchmark workout of the day (WOD), considering differences by sex and training experience;
- iii) To characterize the acute physiological and neuromuscular responses elicited by a standardized WOD and to determine how these responses differ according to sex and training experience.

The first study synthesized the existing evidence on the physiological and biomechanical demands of CrossFit. The review confirmed that CrossFit is a multimodal, high-intensity training (HIT) modality capable of eliciting improvements in maximal strength, hypertrophy, muscular endurance, and cardiorespiratory capacity (Claudino et al., 2018; Dominski et al., 2021; Meier et al., 2023). However, the literature revealed considerable methodological heterogeneity, with most studies assessing either physiological or biomechanical responses in isolation (Buther et al., 2015; Martínez-Gómez et al., 2019; Mangine et al., 2020). This fragmentation limited the capacity to integrate findings and totally understand performance determinants in WODs. Furthermore, few studies explicitly examined individual characteristics such as sex or training experience, despite evidence that these factors influence physiological responses (Dexheimer et al., 2019; Schlegel & Křehký, 2022; Zeitz et al., 2020). Therefore, the systematic review highlighted the need for integrative experimental designs that combine domains and account for subgroup differences when investigating CrossFit performance.

Building on these findings, the second study experimentally examined predictors of performance in the benchmark WOD Fran. Both physiological variables, including VO_2max , ventilatory thresholds, and blood lactate accumulation, and biomechanical measures, such as one-repetition maximum (1RM), countermovement jump (CMJ), and power output, emerged as significant contributors to performance time (Butcher et al., 2015; Martínez-Gómez et al., 2019; Mangine et al., 2020; Zeitz et al., 2020). These results align with previous research in fitness and HIIT, where aerobic capacity and neuromuscular function complementarily determine performance outcomes (Bellar et al., 2015; Drum et al., 2017; Tibana et al., 2018). A novel contribution of this study was the observation that the relative weight of predictors varied across sexes and levels of experience. Men generally relied more on absolute strength and power, whereas women demonstrated advantages in fatigue resistance and pacing ability (Dexheimer et al., 2019; Schlegel & Křehký, 2022). Similarly, more experienced athletes exhibited greater technical efficiency and metabolic control, reducing their dependency on ceiling-level physiological variables, a finding that underscores the importance of accumulated practice in high-skill, multimodal sports (González et al., 2017; Tibana & de Sousa, 2018).

The third study extended this work by examining the acute physiological and neuromuscular responses to a standardized CrossFit workout (Fran) in men, women, experienced, and novice practitioners. Oxygen uptake, ventilation, heart rate, blood lactate concentration, and jump performance were measured before and after the WOD to characterize its immediate physiological and biomechanical impact (Tibana et al., 2018; Mangine et al., 2020). The workout elicited pronounced metabolic and ventilatory stress, accompanied by significant reductions in jump height and power, indicating marked neuromuscular fatigue (Claudino et al., 2018; Drum et al., 2017). Men and more experienced athletes completed the WOD faster and displayed greater ventilatory efficiency and metabolic tolerance, whereas women and novice participants reported higher perceived exertion and larger relative declines in jump performance (Dexheimer et al., 2019; Schlegel & Křehký, 2022). These findings reinforce that acute responses to CrossFit are highly individualized and depend on both sex and training experience, aligning with prior evidence that biological and experiential factors modulate fatigue resistance, pacing, and technical efficiency during high-intensity exercise (Bishop et al., 2008; Sandbakk & Holmberg, 2017).

Taken together, the sequence of studies provides a comprehensive framework for understanding performance in CrossFit. This thesis advances the literature from descriptive analyses of isolated physiological or biomechanical parameters toward

integrative and mechanistic models that account for individual variability. The evidence demonstrates that CrossFit performance and acute responses are multifactorial, context-dependent, and influenced by individual characteristics such as sex and experience. These findings not only enrich the evidence base for CrossFit athletes and coaches but also extend to the broader field of high-intensity training, where similar multimodal demands challenge multiple physiological and neuromuscular systems (Thompson et al., 2020; Buckley et al., 2015).

A methodological strength of the present work was the integration of physiological and biomechanical domains within the same predictive framework. Previous studies typically focused on either metabolic/ventilatory responses or neuromuscular/biomechanical measures, which limited explanatory capacity (Claudino et al., 2018; Martínez-Gómez et al., 2019). By combining VO_2max , ventilatory thresholds, lactate accumulation, strength, and power measures, the present thesis offered a more comprehensive model of WOD performance. In addition, the explicit inclusion of sex and training experience as key individual factors provided a more realistic and nuanced interpretation of results, reducing the bias that can arise from aggregated analyses (Hopkins, 2000; Bouchard & Rankinen, 2001). This integrative and stratified approach illustrates how methodological advances can refine sports performance models, particularly in emerging modalities where complexity and variability are inherent.

Although the thesis was specifically focused on CrossFit, the findings may have broader implications for exercise and sports science. High-intensity training modalities share the multimodal, high-intensity nature of CrossFit, combining strength, endurance, and technical skill within the same training units (Thompson et al., 2020; Buckley et al., 2015). The results suggest that performance in such contexts may depend on the interaction between physiological and biomechanical factors, with potential modulation by sex and experience (Bishop et al., 2008; Sandbakk & Holmberg, 2017). More broadly, this thesis highlights the value of integrative approaches that bridge physiological and biomechanical perspectives and explicitly consider inter-individual variability, offering preliminary insights for refining training prescription and monitoring across athletic populations.

Despite these contributions, some limitations should be acknowledged. First, the experimental studies involved modest sample sizes, which limit statistical power and generalizability. Second, although sex and training experience were included as key analytical factors, other potential influences, such as body composition, psychological

variables, or pacing strategies, were not systematically assessed. Third, the use of a single benchmark WOD (Fran) constrains external validity, as other workouts may emphasize different mechanical and metabolic demands (Mangine et al., 2020; Zeitz et al., 2020). Fourth, the cross-sectional design of the experimental studies precludes causal inference; longitudinal designs are needed to verify whether changes in specific physiological or biomechanical parameters translate into improved performance (Bellar et al., 2015; Drum et al., 2017). Finally, aspects such as technical execution and tactical decision-making, which are likely to influence pacing and efficiency in WODs, were not directly analyzed and warrant further investigation. Overall, these limitations highlight the exploratory character of the findings and the need for continued research using larger, more diverse samples and complementary methodological approaches.

In summary, this doctoral thesis provided preliminary evidence that CrossFit performance may be influenced by the combined contribution of physiological and biomechanical determinants, with potential modulation by sex and training experience. The findings highlight the importance of individualized assessment and tailored training prescription, rather than uniform programming approaches. By integrating systematic review and experimental research while explicitly considering individual characteristics, this thesis proposes a multidimensional perspective for studying performance in CrossFit and related high-intensity training modalities, offering methodological, practical and theoretical insights for both science and practice

Chapter 5. Overall Conclusions

The findings of the present doctoral thesis suggest that performance in CrossFit may be influenced by the interaction between physiological and biomechanical factors, with their relative importance varying according to sex and training experience. Integrating these domains provided a broader and more coherent understanding of potential performance determinants, while emphasizing the need to account for individual variability when interpreting results.

The systematic review indicated that CrossFit elicits adaptations across multiple fitness domains, yet the existing literature remains methodologically heterogeneous and often isolates physiological or biomechanical dimensions. The experimental studies further suggest that variables such as maximal strength, power, oxygen uptake, ventilation, and lactate accumulation may relate to performance in benchmark WOD, although the strength of these associations differed between men and women and across levels of experience.

Overall, the evidence points toward a multifactorial and individualized nature of CrossFit performance. Differences related to sex and training experience appear to influence how athletes respond to and perform during high-intensity multimodal exercise. These results underscore the importance of individualized assessment and training prescription, while recognizing the exploratory character of the findings and the need for confirmation in larger, longitudinal studies.



Chapter 6. Suggestions for Future Research

The results obtained in this thesis represent a first step toward a more comprehensive understanding of the biomechanical and physiological determinants of performance in CrossFit, both in training and competitive contexts. Despite the relevant contributions presented here, many questions remain unanswered, particularly regarding the complex interaction between physiological capacity, biomechanical efficiency, and individual characteristics (e.g., sex and training experience) in determining performance across different Workout of the Day (WOD) formats. Therefore, several directions for future research can be proposed:

- i. Compare the acute physiological and biomechanical responses (e.g., oxygen uptake kinetics, ventilatory thresholds, lactate accumulation, neuromuscular fatigue, and kinematic adaptations) across different WOD structures (e.g., AMRAP vs. time-to-completion vs. EMOM), while equalizing total training volume and work-to-rest ratios, to clarify how task design influences determinants of performance.
- ii. Examine the long-term adaptations to CrossFit-specific training when modulating key programming variables (e.g., volume, intensity, density, exercise order), with a particular focus on whether performance improvements are more strongly driven by physiological (e.g., VO_{2max} , buffering capacity) or biomechanical (e.g., lifting velocity, movement efficiency) adaptations.
- iii. Investigate sex-specific and experience-dependent predictors of CrossFit performance, particularly to determine whether the relative weight of physiological (e.g., aerobic capacity, lactate tolerance) and biomechanical (e.g., barbell velocity, jump performance) determinants varies between men and women or between novice and experienced athletes.
- iv. Develop and validate predictive models of CrossFit performance using integrative approaches that combine multiple domains (e.g., strength, power, aerobic capacity, technical efficiency, recovery dynamics). Machine learning and multivariate statistics could be applied to identify the most robust predictors in different types of WOD.

- v. Explore the time course of recovery following different CrossFit workouts, including neuromuscular, hormonal, metabolic, and perceptual responses, to optimize programming and minimize risk of overtraining or injury.
- vi. Conduct longitudinal studies comparing individualized vs. standardized programming approaches in CrossFit athletes, to assess whether tailoring WODs to sex, anthropometric characteristics, or baseline physiological/biomechanical profiles results in superior adaptations and reduced performance variability.
- vii. Investigate the ecological validity and transferability of laboratory-based predictors of performance (e.g., VO_{2max} treadmill testing, incremental loading tests) to real-world CrossFit competition scenarios, where pacing, task prioritization, and fatigue management may alter performance outcomes.
- viii. Expand research to include broader populations, such as youth, masters, or clinical groups engaging in CrossFit as a form of training, to determine whether the same predictors of performance observed in competitive athletes are relevant for health- or fitness-oriented practitioners.
- ix. Investigating injury epidemiology in relation to biomechanical and physiological demands, clarifying whether specific performance determinants (e.g., lifting velocity, fatigue-induced technique breakdown, insufficient recovery) are associated with increased risk, and how monitoring strategies could be used preventively.

Chapter 7. References

Resumo Alargado

- Butcher, S. J., Neyedly, T. J., Horvey, K. J., & Benko, C. R. (2015). Do physiological measures predict selected CrossFit® benchmark performance? *Open Access Journal of Sports Medicine*, 6, 241–247. <https://doi.org/10.2147/OAJSM.S88265>
- Claudino, J. G., Gabbett, T. J., Bourgeois, F., de Sá Souza, H., Miranda, R. C., Mezêncio, B., Soncin, R., Cardoso Filho, C. A., Bottaro, M., Hernandez, A. J., Amadio, A. C., & Serrão, J. C. (2018). CrossFit overview: Systematic review and meta-analysis. *Sports Medicine – Open*, 4(11). <https://doi.org/10.1186/s40798-018-0124-5>
- Dexheimer, J. D., Schroeder, E. T., Sawyer, B. J., Pettitt, R. W., Aguinaldo, A. L., & Torrence, W. A. (2019). Physiological performance predictors in recreational male and female CrossFit athletes. *Sports*, 7(3), 93. <https://doi.org/10.3390/sports7030093>
- Dominski, F. H., Serafim, T. T., Siqueira, T. C., Andrade, A., & Vilarino, G. T. (2021). Physical and psychosocial benefits of CrossFit® training: A systematic review. *Sport Sciences for Health*, 17(3), 409–420. <https://doi.org/10.1007/s11332-020-00691-5>
- Mangine, G. T., Tankersley, J. E., McDougale, J. M., Velazquez, N., Roberts, M. D., Esmat, T. A., VanDusseldorp, T. A., & Feito, Y. (2020). Predictors of CrossFit Open performance. *Sports*, 8(7), 102. <https://doi.org/10.3390/sports8070102>
- Martínez-Gómez, R., Valenzuela, P. L., Alejo, L. B., Gil-Cabrera, J., Montalvo-Pérez, A., Talavera, E., Lucia, A., & Barranco-Gil, D. (2019). Physiological predictors of competition performance in CrossFit athletes. *International Journal of Environmental Research and Public Health*, 17(2), 369. <https://doi.org/10.3390/ijerph17020369>
- Meier, R., Titze, S., & Wäsche, H. (2023). Health and performance outcomes of CrossFit: A systematic review. *Frontiers in Sports and Active Living*, 5, 1033428. <https://doi.org/10.3389/fspor.2023.1033428>
- Schlegel, P., & Křehký, J. (2022). Effect of experience and sex on CrossFit performance predictors. *Sports*, 10(2), 27. <https://doi.org/10.3390/sports1002002>

Zeitz, E. K., Cook, L. F., Dexheimer, J. D., & Goins, J. (2020). Physiological and anthropometric predictors of CrossFit performance. *Sports*, 8(6), 85. <https://doi.org/10.3390/sports8060085>

Chapter 1. General Introduction

Aravena-Sagardia, P., Barramuño-Medina, M., Vásquez, B., Pichinao, S., Sepúlveda, P., Herrera-Valenzuela, T., Hernandez-Martinez, J., Levín-Catrilao, Á., Villagrán-Silva, F., Vásquez-Carrasco, E., Branco, B., Sandoval, C., & Valdés-Badilla, P. (2025). Effects of a CrossFit Training Program on Body Composition and Physical Fitness in Novice and Advanced Practitioners: An Inter-Individual Analysis. *Applied Sciences*. <https://doi.org/10.3390/app15073554>.

Butcher, S. J., Neyedly, T. J., Horvey, K. J., & Benko, C. R. (2015). Do physiological measures predict selected CrossFit® benchmark performance? *Open Access Journal of Sports Medicine*, 6, 241–247. <https://doi.org/10.2147/OAJSM.S88265>

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

Claudino, J. G., Gabbett, T. J., Bourgeois, F., de Sá Souza, H., Miranda, R. C., Mezêncio, B., Soncin, R., Cardoso Filho, C. A., Bottaro, M., Hernandez, A. J., Amadio, A. C., & Serrão, J. C. (2018). CrossFit overview: Systematic review and meta-analysis. *Sports Medicine – Open*, 4(11). <https://doi.org/10.1186/s40798-018-0124-5>

Cosgrove, S., Crawford, D., & Heinrich, K. (2019). Multiple Fitness Improvements Found after 6-Months of High Intensity Functional Training. *Sports*, 7. <https://doi.org/10.3390/sports7090203>.

Dominski, F. H., Serafim, T. T., Siqueira, T. C., Andrade, A., & Vilarino, G. T. (2021). Physical and psychosocial benefits of CrossFit® training: A systematic review. *Sport Sciences for Health*, 17(3), 409–420. <https://doi.org/10.1007/s11332-020-00691-5>

Glassman, G. (2007). *Understanding CrossFit*. *CrossFit Journal*, 56, 1–2. Retrieved from <https://journal.crossfit.com>

Dominski, F. H., Tibana, R. A., & Andrade, A. (2022). “functional fitness training”, crossfit, himt, or hift: what is the preferable terminology?. *Frontiers in Sports and Active Living*, 4. <https://doi.org/10.3389/fspor.2022.882195>

Eather, N., Morgan, P., & Lubans, D. (2016). Improving health-related fitness in adolescents: the CrossFit Teens™ randomised controlled trial. *Journal of Sports Sciences*, 34, 209 - 223. <https://doi.org/10.1080/02640414.2015.1045925>.

- Feito, Y., Heinrich, K. M., Butcher, S., & Poston, W. S. C. (2018). High-intensity functional training (hift): definition and research implications for improved fitness. *Sports*, 6(3), 76. <https://doi.org/10.3390/sports6030076>
- Mangine, G. T., Tankersley, J. E., McDougle, J. M., Velazquez, N., Roberts, M. D., Esmat, T. A., VanDusseldorp, T. A., & Feito, Y. (2020). Predictors of CrossFit Open performance. *Sports*, 8(7), 102. <https://doi.org/10.3390/sports8070102>
- Martínez-Gómez, R., Valenzuela, P. L., Alejo, L. B., Gil-Cabrera, J., Montalvo-Pérez, A., Talavera, E., Lucia, A., & Barranco-Gil, D. (2019). Physiological predictors of competition performance in CrossFit athletes. *International Journal of Environmental Research and Public Health*, 17(2), 369. <https://doi.org/10.3390/ijerph17020369>
- Mehrab, M., Wágner, R., Vuurberg, G., Gouttebauge, V., Vos, R. d., & Mathijssen, N. M. C. (2022). Risk factors for musculoskeletal injury in crossfit: a systematic review. *International Journal of Sports Medicine*, 44(04), 247-257. <https://doi.org/10.1055/a-1953-6317>
- Meier, R., Titze, S., & Wäsche, H. (2023). Health and performance outcomes of CrossFit: A systematic review. *Frontiers in Sports and Active Living*, 5, 1033428. <https://doi.org/10.3389/fspor.2023.1033428>
- Pritchard, H. J., Keogh, J., & Winwood, P. (2020). Tapering practices of elite crossfit athletes. *International Journal of Sports Science & Coaching*, 15(5-6), 753-761. <https://doi.org/10.1177/1747954120934924>
- Schlie, J., Brandt, T., & Schmidt, A. (2023). StartXFit—Nine Months of CrossFit® Intervention Enhance Cardiorespiratory Fitness and Well-Being in CrossFit Beginners. *Physiologia*. <https://doi.org/10.3390/physiologia3040036>.
- Tibana, R. A., Neto, I. V. d. S., Sousa, N. M. F. d., Romeiro, C., Hanai, A., Brandão, H. C. P., ... & Voltarelli, F. A. (2021). Local muscle endurance and strength are the best predictors of crossfit open 2020 in amateur athletes.. <https://doi.org/10.20944/preprints202106.0034.v1>
- Zeitz, E. K., Cook, L. F., Dexheimer, J. D., & Goins, J. (2020). Physiological and anthropometric predictors of CrossFit performance. *Sports*, 8(6), 85. <https://doi.org/10.3390/sports8060085>

Chapter 2. Literature Review

- Ambroży, T., Rydzik, Ł., Kwiatkowski, A., Spieszny, M., Ambroży, D., Rejman, A., Koteja, A., Jaszczur-Nowicki, J., Duda, H., & Czarny, W. (2022). Effect of CrossFit Training on Physical Fitness of Kickboxers. *International Journal of Environmental Research and Public Health*, *19*(8), 4526. <https://doi.org/10.3390/ijerph19084526>
- Bachero-Mena, B., & González-Badillo, J. J. (2021). Mechanical and Metabolic Responses during High-intensity Training in Elite 800-m Runners. *International Journal of Sports Medicine*, *42*(04), 350–356. <https://doi.org/10.1055/a-1273-8564>
- Banyard, H. G., Nosaka, K., & Haff, G. G. (2017). Reliability and Validity of the Load–Velocity Relationship to Predict the 1RM Back Squat. *Journal of Strength & Conditioning Research*, *31*(7), 1897–1904. <https://doi.org/10.1519/JSC.0000000000001657>
- Barreto, A. C., Leitão, L., Vianna, J. M., Poderoso, R., Reis, V. M., Cirilo-Sousa, M. S. ... & Novaes, J. S. (2024). Do Men and Women Differ in Hematological Adaptations to 24 Weeks of CrossFit Training?. *Journal of Human Kinetics*, *90*, 101–110. <https://doi.org/10.5114/jhk/170885>
- Bellar, D., Hatchett, A., Judge, L., Breaux, M., & Marcus, L. (2015). The relationship of aerobic capacity, anaerobic peak power and experience to performance in CrossFit exercise. *Biology of Sport*, *32*(4), 315–320. <https://doi.org/10.5604/20831862.1174771>
- Brandt, T., Heinz, E., Klaaßen, Y., Limbara, S., Mörsdorf, M., Schinköthe, T., & Schmidt, A. (2022). MedXFit—Effects of 6 months CrossFit® in sedentary and inactive employees: A prospective, controlled, longitudinal, intervention study. *Health Science Reports*, *5*(5), e749. <https://doi.org/10.1002/hsr2.749>
- Brogna, L., Mazzotti, A., Rossi, F., Lamia, F., Artioli, E., Faldini, C., & Traina, F. (2023). Using Wearable Inertial Sensors to Monitor Effectiveness of Different Types of Customized Orthoses during CrossFit® Training. *Sensors*, *23*(3), 1636. <https://doi.org/10.3390/s23031636>
- Butcher, S., Judd, T., Benko, C., Horvey, K., & Pshyk, A. (2015a). Relative Intensity of Two Types of Crossfit Exercise: Acute Circuit and High-Intensity Interval Exercise. *Journal of Fitness Research*, *4*(2), 3–15.
- Butcher, S., Neyedly, T., Horvey, K., & Benko, C. (2015b). Do physiological measures predict selected CrossFit® benchmark performance? *Open Access Journal of Sports Medicine*, *6*, 241–247. <https://doi.org/10.2147/OAJSM.S88265>

- Carreker, J. D., & Grosicki, G. J. (2020). Physiological Predictors of Performance on the CrossFit “Murph” Challenge. *Sports*, 8(7), 92. <https://doi.org/10.3390/sports8070092>
- Cejudo, A. (2022). Predicting the Clean Movement Technique in Crossfit® Athletes Using an Optimal Upper-Limb Range of Motion: A Prospective Cohort Study. *International Journal of Environmental Research and Public Health*, 19(19), 12985. <https://doi.org/10.3390/ijerph191912985>
- Claudino, J. G., Gabbett, T. J., Bourgeois, F., Souza, H. D. S., Miranda, R. C., Mezêncio, B., Soncin, R., Cardoso Filho, C. A., Bottaro, M., Hernandez, A. J., Amadio, A. C., & Serrão, J. C. (2018). CrossFit Overview: Systematic Review and Meta-analysis. *Sports Medicine - Open*, 4(1), 11. <https://doi.org/10.1186/s40798-018-0124-5>
- Cosgrove, S. J., Crawford, D. A., & Heinrich, K. M. (2019). Multiple Fitness Improvements Found after 6-Months of High Intensity Functional Training. *Sports*, 7(9), 203. <https://doi.org/10.3390/sports7090203>
- DeBeliso, M., Boham, M., Harris, C., Carson, C., Berning, J. M., Sevene, T., & Adams, K. J. (2015). Grip and body strength measures in the mature adult: A brief report. *International Journal of Science and Engineering Investigations*, 4(37), 83–86.
- Dexheimer, J. D., Schroeder, E. T., Sawyer, B. J., Pettitt, R. W., Aguinaldo, A. L., & Torrence, W. A. (2019). Physiological Performance Measures as Indicators of CrossFit® Performance. *Sports*, 7(4), 93. <https://doi.org/10.3390/sports7040093>
- Di Michele, R., Del Curto, L., & Merni, F. (2012). Mechanical and metabolic responses during a high-intensity circuit training workout in competitive runners. *Journal of Sports Medicine and Physical Fitness*, 52(1), 33–39.
- Dominski, F. H., Serafim, T. T., Siqueira, T. C., & Andrade, A. (2021). Psychological variables of CrossFit participants: A systematic review. *Sport Sciences for Health*, 17(1), 21–41. <https://doi.org/10.1007/s11332-020-00685-9>
- Faelli, E., Bisio, A., Codella, R., Ferrando, V., Perasso, L., Panasci, M., Saverino, D., & Ruggeri, P. (2020). Acute and Chronic Catabolic Responses to CrossFit® and Resistance Training in Young Males. *International Journal of Environmental Research and Public Health*, 17(19), 7172. <https://doi.org/10.3390/ijerph17197172>
- Feito, Y., Giardina, M. J., Butcher, S., & Mangine, G. T. (2019). Repeated anaerobic tests predict performance among a group of advanced CrossFit-trained athletes. *Applied Physiology, Nutrition, and Metabolism*, 44(7), 727–735. <https://doi.org/10.1139/apnm-2018-0509>
- Fernández-Fernández, J., Sabido, R., Moya, D., Sarabia Marín, J. M., & Moya, M. (2015). Acute physiological responses during crossfit® workouts. *European Journal of Human Movement*, 35, 114–124.

- Ferreira, I. C., Almeida Souza, M., Miarka, B., Cardoso, R., Badaró, M., Brito, C., & Carvalho Barbosa, A. W. (2020). Interquartile differences in biomechanical parameters in CrossFit® athletes during deep squats with submaximal load until fatigue. *Journal of Sports Medicine and Physical Fitness*, *60*(9), 1216–1222. <https://doi.org/10.23736/S0022-4707.20.10845-4>
- Fisker, F. Y., Kildegaard, S., Thygesen, M., Grosen, K., & Pfeiffer-Jensen, M. (2017). Acute tendon changes in intense CrossFit workout: An observational cohort study. *Scandinavian Journal of Medicine & Science in Sports*, *27*(11), 1258–1262. <https://doi.org/10.1111/sms.12781>
- García-Pinillos, F., Soto-Hermoso, V. M., & Latorre-Román, P. A. (2017). How does high-intensity intermittent training affect recreational endurance runners? Acute and chronic adaptations: A systematic review. *Journal of Sport and Health Science*, *6*(1), 54–67. <https://doi.org/10.1016/j.jshs.2016.08.010>
- Gardiner, B., Devereux, G., & Beato, M. (2020). Injury risk and injury incidence rates in CrossFit. *Journal of Sports Medicine and Physical Fitness*, *60*(7), 1005–1013. <https://doi.org/10.23736/S0022-4707.20.10615-7>
- Gianzina, E. A., & Kassotaki, O. A. (2019). The benefits and risks of the high-intensity CrossFit training. *Sport Sciences for Health*, *15*(1), 21–33. <https://doi.org/10.1007/s11332-018-0521-7>
- Glassman, G. (2003). Benchmark workouts. *CrossFit Journal*, *13*, 1–5.
- Glassman, G. (2010). *The crossfit training guide* (Vol. 30). CrossFit.
- Gómez-Landero, L. A., & Frías-Menacho, J. M. (2020). Analysis of Morphofunctional Variables Associated with Performance in Crossfit® Competitors. *Journal of Human Kinetics*, *73*(1), 83–91. <https://doi.org/10.2478/hukin-2019-0134>
- González-Badillo, J. J., Sánchez-Medina, L., Ribas-Serna, J., & Rodríguez-Rosell, D. (2022). Toward a New Paradigm in Resistance Training by Means of Velocity Monitoring: A Critical and Challenging Narrative. *Sports Medicine - Open*, *8*(1), 118. <https://doi.org/10.1186/s40798-022-00513-z>
- Haynes, E., & Debeliso, M. (2019). The relationship between CrossFit performance and grip strength. *Turkish Journal of Kinesiology*, *5*(1), 15–21. <https://doi.org/10.31459/turkjin.515874>
- Heinrich, K. M., Becker, C., Carlisle, T., Gilmore, K., Hauser, J., Frye, J., & Harms, C. A. (2015). High-intensity functional training improves functional movement and body composition among cancer survivors: A pilot study. *European Journal of Cancer Care*, *24*(6), 812–817. <https://doi.org/10.1111/ecc.12338>
- Jacob, N., Novaes, J. S., Behm, D. G., Vieira, J. G., Dias, M. R., & Vianna, J. M. (2020). Characterization of Hormonal, Metabolic, and Inflammatory Responses in

- CrossFit® Training: A Systematic Review. *Frontiers in Physiology*, 11, 1001. <https://doi.org/10.3389/fphys.2020.01001>
- Kićanović, L., Živanović, B., Vukadinović Jurišić, M., & Obradović, J. (2022). Effects of CrossFit training program and traditional gym training on morphological characteristics of men. *Exercise and Quality of Life*, 14(2), 13–19. <https://doi.org/10.31382/eqol.221202>
- Klimek, C., Ashbeck, C., Brook, A. J., & Durall, C. (2018). Are Injuries More Common With CrossFit Training Than Other Forms of Exercise? *Journal of Sport Rehabilitation*, 27(3), 295–299. <https://doi.org/10.1123/jsr.2016-0040>
- Kluszczewicz, B., Snarr, R. L., & Esco, M. (2014). Metabolic and cardiovascular response to the CrossFit workout “Cindy”: A pilot study. *Journal of Sport and Human Performance*, 2(2), 1–9. <https://doi.org/10.12922/jshp.v2i2.38>
- Knapik, J. J. (2015). Extreme Conditioning Programs: Potential Benefits and Potential Risks. *Journal of Special Operations Medicine*, 15(3), 108. <https://doi.org/10.55460/8J8E-2Q8D>
- Maia, N. M., Assumpção, C. O., Andrade, A. D., Fernandes, R. J., & Medeiros, A. I. A. (2019). Neuromuscular and autonomic responses during a CrossFit® competition: A case study. *TRENDS in Sport Sciences*, 26(4), 165–170. <https://doi.org/10.23829/TSS.2019.26.4-4>
- Mangine, G. T., Grundlingh, N., & Feito, Y. (2023). Differential Improvements Between Men and Women in Repeated Crossfit® Open Workouts. *PLoS One*, 18(11), e0283910. <https://doi.org/10.1371/journal.pone.0283910>
- Mangine, G. T., Stratton, M. T., Almeda, C. G., Roberts, M. D., Esmat, T. A., VanDusseldorp, T. A., & Feito, Y. (2020). Physiological differences between advanced CrossFit athletes, recreational CrossFit participants, and physically-active adults. *PLoS One*, 15(4), e0223548. <https://doi.org/10.1371/journal.pone.0223548>
- Marshall, J., Bishop, C., Turner, A., & Haff, G. G. (2021). Optimal Training Sequences to Develop Lower Body Force, Velocity, Power, and Jump Height: A Systematic Review with Meta-Analysis. *Sports Medicine*, 51(6), 1245–1271. <https://doi.org/10.1007/s40279-021-01430-z>
- Martínez-Gómez, R., Valenzuela, P. L., Barranco-Gil, D., Moral-González, S., García-González, A., & Lucia, A. (2019). Full-Squat as a Determinant of Performance in CrossFit. *International Journal of Sports Medicine*, 40(09), 592–596. <https://doi.org/10.1055/a-0960-9717>
- Maté-Muñoz, J. L., Hernández Loougedo, J., Barba-Ruiz, M., Cañuelo Marquez, A., Guodemar-Pérez, J., Fernández, P., Lozano, M. C., Alonso-Melero, R., Sánchez-Calabuig, M., Ruíz-López, M., Jesús, F., & Garnacho-Castaño, M. (2018).

- Cardiometabolic and Muscular Fatigue Responses to Different CrossFit® Workouts. *Journal of Sports Science & Medicine*, 17, 668–679.
- Maté-Muñoz, J. L., Lougedo, J. H., Barba, M., García-Fernández, P., Garnacho-Castaño, M. V., & Domínguez, R. (2017). Muscular fatigue in response to different modalities of CrossFit sessions. *PLoS One*, 12(7), e0181855. <https://doi.org/10.1371/journal.pone.0181855>
- McHugh, M. L. (2012). Interrater reliability: The kappa statistic. *Biochemia Medica*, 22(3), 276–282. <https://doi.org/10.11613/BM.2012.031>
- Mehrab, M., Wagner, R. K., Vuurberg, G., Gouttebauge, V., De Vos, R.-J., & Mathijssen, N. M. C. (2023). Risk Factors for Musculoskeletal Injury in CrossFit: A Systematic Review. *International Journal of Sports Medicine*, 44(04), 247–257. <https://doi.org/10.1055/a-1953-6317>
- Meier, N., Schlie, J., & Schmidt, A. (2023). CrossFit®: ‘Unknowable’ or Predictable?—A Systematic Review on Predictors of CrossFit® Performance. *Sports*, 11(6), 112. <https://doi.org/10.3390/sports11060112>
- Menargues-Ramírez, R., Sospedra, I., Holway, F., Hurtado-Sánchez, J. A., & Martínez-Sanz, J. M. (2022). Evaluation of Body Composition in CrossFit® Athletes and the Relation with Their Results in Official Training. *International Journal of Environmental Research and Public Health*, 19(17), 11003. <https://doi.org/10.3390/ijerph191711003>
- Meyer, J., Morrison, J., & Zuniga, J. (2017). The Benefits and Risks of CrossFit: A Systematic Review. *Workplace Health & Safety*, 65(12), 612–618. <https://doi.org/10.1177/2165079916685568>
- Milanović, Z., Sporiš, G., & Weston, M. (2015). Effectiveness of High-Intensity Interval Training (HIT) and Continuous Endurance Training for VO_{2max} Improvements: A Systematic Review and Meta-Analysis of Controlled Trials. *Sports Medicine*, 45(10), 1469–1481. <https://doi.org/10.1007/s40279-015-0365-0>
- Munn, Z., Stone, J. C., Aromataris, E., Klugar, M., Sears, K., Leonardi-Bee, J., & Barker, T. H. (2023). Assessing the risk of bias of quantitative analytical studies: Introducing the vision for critical appraisal within JBI systematic reviews. *JBI Evidence Synthesis*, 21(3), 467–471. <https://doi.org/10.11124/JBIES-22-00224>
- Naderi, A., Shokri, M., Mokaberian, M., & Tranaeus, U. (2025). Understanding Sports Injury Risks in CROSSFIT: A Prospective Cohort Study on Athletic Demographics, Training Profiles, Injury History, and Psychological Factors. *Scandinavian Journal of Medicine & Science in Sports*, 35(8), e70100. <https://doi.org/10.1111/sms.70100>
- Nicolay, R. W., Moore, L. K., DeSena, T. D., & Dines, J. S. (2022). Upper Extremity Injuries in CrossFit Athletes—A Review of the Current Literature. *Current Reviews*

- in *Musculoskeletal Medicine*, 15(5), 402–410. <https://doi.org/10.1007/s12178-022-09781-4>
- Oliver-López, A., García-Valverde, A., & Sabido, R. (2024). Standardized vs. Relative Intensity in CrossFit. *International Journal of Sports Medicine*, 45(04), 301–308. <https://doi.org/10.1055/a-2204-2953>
- Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., ... & Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ (Clinical Research Ed.)*, 372, n71. <https://doi.org/10.1136/bmj.n71>
- Pareja-Blanco, F., Alcazar, J., Sánchez-Valdepeñas, J., Cornejo-Daza, P. J., Piqueras-Sanchiz, F., Mora-Vela, R., Sánchez-Moreno, M., Bachero-Mena, B., Ortega-Becerra, M., & Alegre, L. M. (2020). Velocity Loss as a Critical Variable Determining the Adaptations to Strength Training. *Medicine & Science in Sports & Exercise*, 52(8), 1752–1762. <https://doi.org/10.1249/mss.0000000000002295>
- Polydorou, R., Kyriacou-Rossi, A., Hadjipantelis, A., Ioannides, C., & Zaras, N. (2024). The Role of Physical Fitness on FRAN CrossFit® Workout Performance. *Applied Sciences*, 14(8), 3317. <https://doi.org/10.3390/app14083317>
- Rios, M., Pyne, D. B., & Fernandes, R. J. (2024). The Effects of CrossFit® Practice on Physical Fitness and Overall Quality of Life. *International Journal of Environmental Research and Public Health*, 22(1), 19. <https://doi.org/10.3390/ijerph22010019>
- Rodríguez, M. Á., García-Calleja, P., Terrados, N., Crespo, I., Del Valle, M., & Olmedillas, H. (2022). Injury in CrossFit®: A Systematic Review of Epidemiology and Risk Factors. *Physician and Sportsmedicine*, 50(1), 3–10. <https://doi.org/10.1080/00913847.2020.1864675>
- Sánchez-Medina, L., & González-Badillo, J. (2011). Velocity loss as an indicator of neuromuscular fatigue during resistance training. *Medicine & Science in Sports & Exercise*, 43(9), 1725–1734. <https://doi.org/10.1249/MSS.ob013e318213f880>
- Sauvé, B., Haugan, M., & Paulsen, G. (2024). Physical and Physiological Characteristics of Elite CrossFit Athletes. *Sports*, 12(6), 162. <https://doi.org/10.3390/sports12060162>
- Schlegel, P. (2020). CrossFit® Training Strategies from the Perspective of Concurrent Training: A Systematic Review. *Journal of Sports Science & Medicine*, 19(4), 670–680.

- Schlegel, P., & Křehký, A. (2022). Performance Sex Differences in CrossFit®. *Sports*, 10(11), 165. <https://doi.org/10.3390/sports10110165>
- Schlie, J., Brandt, T., & Schmidt, A. (2023). StartXFit—Nine Months of CrossFit® Intervention Enhance Cardiorespiratory Fitness and Well-Being in CrossFit Beginners. *Physiologia*, 3(4), 494–509. <https://doi.org/10.3390/physiologia3040036>
- Schoenfeld, B. J., Grgic, J., Ogborn, D., & Krieger, J. W. (2017). Strength and Hypertrophy Adaptations Between Low- vs. High-Load Resistance Training: A Systematic Review and Meta-analysis. *Journal of Strength & Conditioning Research*, 31(12), 3508–3523. <https://doi.org/10.1519/JSC.0000000000002200>
- Seo, M., Park, T., & Jung, H. C. (2024). Sex Differences in Heart Rate Variability and Vascular Function Following High-Intensity Interval Training in Young Adults. *Journal of Human Kinetics*, 90, 89–100. <https://doi.org/10.5114/jhk/170964>
- Shaw, T., & Sergent, A. (2019). Improved Performance After Gluteus Complex Activation in a CrossFit Athlete Presenting With Knee Pain. *Journal of Chiropractic Medicine*, 18(4), 343–347. <https://doi.org/10.1016/j.jcm.2019.12.003>
- Shim, S. S., Confino, J. E., & Vance, D. D. (2023). Common Orthopaedic Injuries in CrossFit Athletes. *Journal of the American Academy of Orthopaedic Surgeons*, 31(11), 557–564. <https://doi.org/10.5435/JAAOS-D-22-01219>
- Sousa, A., Santos, G., Reis, T., Valerino, A., Del Rosso, S., & Boulosa, D. (2016). Differences in Physical Fitness between Recreational CrossFit® and Resistance Trained Individuals. *Journal of Exercise Physiology Online*, 19(5), 112–122.
- Tafari, S., Notarnicola, A., Manno, A., Ferretti, F., & Moretti, B. (2019). CrossFit athletes exhibit high symmetry of fundamental movement patterns. A cross-sectional study. *Muscle Ligaments and Tendons Journal*, 06(01), 157. <https://doi.org/10.32098/mltj.01.2016.19>
- Tibana, R. A., De Sousa, N. M. F., Prestes, J., & Voltarelli, F. A. (2018). Lactate, Heart Rate and Rating of Perceived Exertion Responses to Shorter and Longer Duration CrossFit® Training Sessions. *Journal of Functional Morphology and Kinesiology*, 3(4), 60. <https://doi.org/10.3390/jfmk3040060>
- Tibana, R. A., De Sousa Neto, I. V., Sousa, N. M. F. D., Romeiro, C., Hanai, A., Brandão, H., Dominski, F. H., & Voltarelli, F. A. (2021). Local Muscle Endurance and Strength Had Strong Relationship with CrossFit® Open 2020 in Amateur Athletes. *Sports*, 9(7), 98. <https://doi.org/10.3390/sports9070098>
- Waryasz, G., Suric, V., Daniels, A., Gil, J., & Ebersson, C. (2016). CrossFit® instructor demographics and practice trends. *Orthopedic Review*, 8(4), 106–110. <https://doi.org/10.4081/or.2016.6571>

- Weisenthal, B. M., Beck, C. A., Maloney, M. D., DeHaven, K. E., & Giordano, B. D. (2014). Injury Rate and Patterns Among CrossFit Athletes. *Orthopaedic Journal of Sports Medicine*, 2(4), 2325967114531177. <https://doi.org/10.1177/2325967114531177>
- Yue, T., Su, H., Cheng, M., Wang, Y., Bao, K., & Qi, F. (2025). High-Intensity Interval Training Improves Inhibitory Control and Working Memory in Healthy Young Adults. *Journal of Human Kinetics*, 98, 41–56. <https://doi.org/10.5114/jhk/194498>
- Yüksel, O., Gündüz, B., & Kayhan, M. (2018). Effect of CrossFit Training on Jump and Strength. *Journal of Education and Training Studies*, 7(1), 121. <https://doi.org/10.11114/jets.v7i1.3896>
- Zeit, E. K., Cook, L. F., Dexheimer, J. D., Lemez, S., Leyva, W. D., Terbio, I. Y., Tran, J. R., & Jo, E. (2020). The Relationship between CrossFit® Performance and Laboratory-Based Measurements of Fitness. *Sports*, 8(8), 112. <https://doi.org/10.3390/sports8080112>

Chapter 3. Study 2

- Anderson, F.C.; Pandy, M.G. A Dynamic Optimization Model for the Prediction of Gait. *J. Biomech.* 1993, 26, 155–166. [https://doi.org/10.1016/0021-9290\(93\)90063-J](https://doi.org/10.1016/0021-9290(93)90063-J).
- Batterham, A.M.; Hopkins, W.G. Making Meaningful Inferences about Magnitudes. *Int. J. Sports Physiol. Perform.* 2006, 1, 50–57. <https://doi.org/10.1123/ijsp.1.1.50>.
- Behm, D.G.; Young, J.D.; Whitten, J.H.D.; Reid, J.C.; Quigley, P.J.; Low, J.; Li, Y.; Lima, C.D.; Hodgson, D.D.; Chaouachi, A.; et al. Effectiveness of Traditional Strength vs. Power Training on Muscle Strength, Power and Speed with Youth: A Systematic Review and Meta-Analysis. *Front. Physiol.* 2017, 8, 423. <https://doi.org/10.3389/fphys.2017.00423>.
- Bellar, D.; Hatchett, A.; Judge, L.; Breaux, M.; Marcus, L. The Relationship of Aerobic Capacity, Anaerobic Peak Power and Experience to Performance in HIT Exercise. *Biol. Sport* 2015, 32, 315–320.
- Benavides-Ubric, A.; Díez-Fernández, M.D.; Rodríguez-Pérez, M.A.; Ortega-Becerra, M.; Pareja Blanco, F. Analysis of the Load–Velocity Relationship in Deadlift Exercise. *J. Sports Sci. Med.* 2020, 19, 452–459.
- Benjamini, Y.; Hochberg, Y. Controlling the False Discovery Rate: A Practical and Powerful Approach to Multiple Testing. *J. R. Stat. Soc. Ser. B Stat. Methodol.* 1995, 57, 289–300. <https://doi.org/10.1111/j.2517-6161.1995.tb02031.x>.
- Blair, M.L. Sex-Based Differences in Physiology: What Should We Teach in the Medical Curriculum? *Adv. Physiol. Educ.* 2007, 31, 23–25. <https://doi.org/10.1152/advan.00118.2006>.

- Borg, G.A. Psychophysical Bases of Perceived Exertion. *Med. Sci. Sports Exerc.* 1982, 14, 377–381. <https://doi.org/10.1249/00005768-198205000-00012>.
- Butcher, S.; Neyedly, T.; Horvey, K.J.; Benko, C. Do Physiological Measures Predict Selected CrossFit Benchmark Performance? *J. Sports Med.* 2015, 241. <https://doi.org/10.2147/oajsm.s88265>.
- Cataldi, S.; Francavilla, V.; Bonavolontà, V.; Florio, O.; Carvutto, R.; Candia, M.; Fischetti, F. Proposal for a Fitness Program in the School Setting during the COVID-19 Pandemic: Effects of an 8-Week CrossFit Program on Psychophysical Well-Being in Healthy Adolescents. *Int. J. Environ. Res. Public Health* 2021, 18, 3141. <https://doi.org/10.3390/ijerph18063141>.
- Claudino, J.G.; Gabbett, T.J.; Bourgeois, F.; Souza, H.d.S.; Miranda, R.C.; Mezêncio, B.; Soncin, R.; Filho, C.A.C.; Bottaro, M.; Hernandez, A.J.; et al. CrossFit Overview: Systematic Review and Meta-Analysis. *Sports Med. Open* 2018, 4, 11. <https://doi.org/10.1186/s40798-018-0124-5>.
- Cohen, J. *Statistical Power Analysis for the Behavioral Sciences*, 2nd ed.; Lawrence Erlbaum Associates: Mahwah, NJ, USA, 1988.
- Cruz-Díaz, D.; Hita-Contreras, F.; Martínez-Amat, A.; Aibar-Almazán, A.; Kim, K. Ankle-Joint Self-Mobilization and CrossFit Training in Patients with Chronic Ankle Instability: A Randomized Controlled Trial. *J. Athl. Train.* 2020, 55, 159–168. <https://doi.org/10.4085/1062-6050-181-18>.
- Dexheimer, J.D.; Schroeder, E.T.; Sawyer, B.J.; Pettitt, R.W.; Aguinaldo, A.L.; Torrence, W.A. Physiological Performance Measures as Indicators of CrossFit® Performance. *Sports* 2019, 7, 93. <https://doi.org/10.3390/sports7040093>.
- Dominski, F.; Serafim, T.; Siqueira, T.; Andrade, A. Psychological Variables of CrossFit Participants: A Systematic Review. *Sport Sci. Health* 2020, 17, 21–41. <https://doi.org/10.1007/s11332-020-00685-9>.
- Édouard, P.; Feddermann-Demont, N.; Alonso, J.; Branco, P.; Junge, A. Injury Risk Is Different between Male and Female Athletes during 14 International Athletics Championships. *Br. J. Sports Med.* 2017, 51, 315. <https://doi.org/10.1136/bjsports-2016-097372.81>.
- Feito, Y.; Heinrich, K.M.; Butcher, S.J.; Poston, W.S.C. High-Intensity Functional Training (HIFT): Definition and Research Implications for Improved Fitness. *Sports* 2018, 6, 76. <https://doi.org/10.3390/sports6030076>.
- González-Badillo, J.J.; Sánchez-Medina, L. Movement Velocity as a Measure of Loading Intensity in Resistance Training. *Int. J. Sports Med.* 2010, 31, 347–352.
- González-Hernández, J.M.; García-Ramos, A.; Castaño-Zambudio, A.; Capelo-Ramírez, F.; Marquez, G.; Boullosa, D.; Jiménez-Reyes, P. Mechanical, Metabolic, and

- Perceptual Acute Responses to Different Set Configurations in Full Squat. *J. Strength Cond. Res.* 2020, 34, 1581–1590. PMID: 28700515.
- Grgic, J.; Lazinica, B.; Schoenfeld, B.; Pedisic, Z. Test–Retest Reliability of the One-Repetition Maximum (1RM) Strength Assessment: A Systematic Review. *Sports Med. Open* 2020, 6, 31. <https://doi.org/10.1186/s40798-020-00260-z>.
- Heinrich, K.; Beattie, C.; Crawford, D.; Stoepker, P.; George, J. Non-Traditional Physical Education Classes Improve High School Students' Movement Competency and Fitness: A Mixed-Methods Program Evaluation Study. *Int. J. Environ. Res. Public Health* 2023, 20, 5914.
- Hernández-Belmonte, A.; Buendía-Romero, Á.; Pallares, G.J.; Martínez-Cava, A. Velocity-Based Method in Free-Weight and Machine-Based Training Modalities: The Degree of Freedom Matters. *J. Strength Cond. Res.* 2023, 37, e500–e509.
- Hodžić, D.; D'Hulst, G.; Leuenberger, R.; Arnet, J.; Westerhuis, E.; Roth, R.; Schmidt-Trucksäss, A.; Knaier, R.; Wagner, J. Physiological Profiles of Male and Female CrossFit Athletes. *bioRxiv* 2023. <https://doi.org/10.1101/2023.10.11.561828>.
- Hunter, S.K.; Angadi, S.S.; Bhargava, A.; Harper, J.; Hirschberg, A.L.; Levine, B.D.; Moreau, K.L.; Nokoff, N.J.; Stachenfeld, N.S.; Bermon, S. The Biological Basis of Sex Differences in Athletic Performance: Consensus Statement for the American College of Sports Medicine. *Med. Sci. Sports Exerc.* 2023, 55, 2328–2360. <https://doi.org/10.1249/mss.0000000000003300>.
- Lakens, D. Calculating and Reporting Effect Sizes to Facilitate Cumulative Science: A Practical Primer for t-Tests and ANOVAs. *Front. Psychol.* 2013, 4. <https://doi.org/10.3389/fpsyg.2013.00863>.
- Langford, E.L.; Bergstrom, H.C.; Lanham, S.; Eastman, A.Q.; Best, S.; Ma, X.; Abel, M.G. Evaluation of Work Efficiency in Structural Firefighters. *J. Strength Cond. Res.* 2023, 37, 2457–2466. <https://doi.org/10.1519/jsc.0000000000004577>.
- Lawson, D.J.; Olmos, A.A.; Stahl, C.A.; Lopes dos Santos, M.; Goodin, J.R.; Dawes, J.J. Validity, Reliability, and Sensitivity of a Commercially Available Velocity Measuring Device when Performing Selected Exercises. *Int. J. Exerc. Sci.* 2024, 17, 1250–1279.
- Lourenco, T.F.; Martins, L.E.B.; Tessutti, L.S.; Brenzikofer, R.; Macedo, D.V. Reproducibility of an Incremental Treadmill VO₂max Test with Gas Exchange Analysis for Runners. *J. Strength Cond. Res.* 2011, 25, 1994–1999. <https://doi.org/10.1519/JSC.ob013e3181e501d6>.
- Mangine, G.; Tankersley, J.; McDougale, J.; Velazquez, N.; Roberts, M.; Esmat, T.; VanDusseldorp, T.A.; Feito, Y. Predictors of CrossFit Open Performance. *Sports* 2020, 8, 102. <https://doi.org/10.3390/sports8070102>.

- Marzano-Felisatti, J.M.; Lucca, L.D.; Luján, J.F.G.; Priego-Quesada, J.I.; Pino-Ortega, J. A Preliminary Investigation about the Influence of WIMU Pro™ Location on Heart Rate Accuracy: A Comparative Study in Cycle Ergometer. *Sensors* 2024, 24, 988. <https://doi.org/10.3390/s24030988>.
- Martínez-Gómez, R.; Valenzuela, L.P.; Alejo, L.; Gil-Cabrera, J.; Montalvo-Pérez, A.; Talavera, E.; Barranco-Gil, D. Physiological Predictors of Competition Performance in CrossFit Athletes. *Int. J. Environ. Res. Public Health* 2020, 17, 3699. <https://doi.org/10.3390/ijerph17103699>.
- Martínez-Gómez, R.; Valenzuela, L.P.; Barranco-Gil, D.; Moral-González, S.; García-González, A.; Lucia, A. Full-Squat as a Determinant of Performance in CrossFit. *Int. J. Sports Med.* 2019, 40, 592–596.
- Martínez-Valência, M.A.; Linthorne, N.P.; Alcaráz, P.E. Effect of Lower Body Explosive Power on Sprint Time in a Sled-Towing Exercise. *Sci. Sports* 2013, 28, e175–e178. <https://doi.org/10.1016/j.scispo.2013.02.004>.
- McLaren, S.J.; Graham, M.; Spears, I.R.; Weston, M. The Sensitivity of Differential Ratings of Perceived Exertion as Measures of Internal Load. *Int. J. Sports Physiol. Perform.* 2016, 11, 404–406. <https://doi.org/10.1123/ijsp.2015-0223>.
- Meier, N.; Schlie, J.; Schmidt, A. CrossFit: ‘Unknowable’ or Predictable?—A Systematic Review on Predictors of CrossFit Performance. *Sports* 2023, 11, 112. <https://doi.org/10.3390/sports11060112>.
- Meyer, J.; Morrison, J.; Zuniga, J. The Benefits and Risks of CrossFit: A Systematic Review. *Workplace Health Saf.* 2017, 65, 612–618.
- O’Neal, C.W.; Mancini, J.A.; DeGraff, A. Contextualizing the Psychosocial Well-Being of Military Members and Their Partners: The Importance of Community and Relationship Provisions. *Am. J. Community Psychol.* 2016, 58, 477–487. <https://doi.org/10.1002/ajcp.12097>.
- Qiu, S.; Alzhab, S.; Picard, G.; Taylor, J.A. Ventilation Limits Aerobic Capacity after Functional Electrical Stimulation Row Training in High Spinal Cord Injury. *Med. Sci. Sports Exerc.* 2016, 48, 1111–1118. <https://doi.org/10.1249/mss.0000000000000880>.
- Rios, M.; Becker, K.M.; Monteiro, A.S.; Fonseca, P.; Pyne, D.B.; Reis, V.M.; Moreira-Gonçalves, D.; Fernandes, R.J. Effect of the Fran CrossFit Workout on Oxygen Uptake Kinetics, Energetics, and Postexercise Muscle Function in Trained CrossFitters. *Int. J. Sports Physiol. Perform.* 2024, 19, 299–306. <https://doi.org/10.1123/ijsp.2023-0201>.
- Sanfilippo, J.; Krueger, D.; Heiderscheid, B.C.; Binkley, N. Dual-Energy X-Ray Absorptiometry Body Composition in NCAA Division I Athletes: Exploration of

- Mass Distribution. *Sports Health* 2019, 11, 453–460. <https://doi.org/10.1177/1941738119861572>.
- Sánchez, O.A.; Hesse, A.S.; Betker, M.R.; Lundstrom, C.J.; Conroy, W.E.; Gao, Z. Cardiovascular Fitness and Associated Comorbidities in an Executive Health Program. *Exerc. Med.* 2022, 6, 5. <https://doi.org/10.26644/em.2022.005>.
- Sánchez-Medina, L.; González-Badillo, J.J. Velocity Loss as an Indicator of Neuromuscular Fatigue during Resistance Training. *Med. Sci. Sports Exerc.* 2011, 43, 1725–1734. <https://doi.org/10.1249/MSS.0b013e318213f880>.
- Sánchez-Medina, L.; Pallarés, J.G.; Pérez, C.E.; Morán-Navarro, R.; González-Badillo, J.J. Estimation of Relative Load from Bar Velocity in the Full Back Squat Exercise. *Sports Med. Int. Open* 2017, 1, E80–E88. <https://doi.org/10.1055/s-0043-102933>.
- Sánchez-Medina, L.; Pérez, C.E.; González-Badillo, J.J. Importance of the Propulsive Phase in Strength Assessment. *Int. J. Sports Med.* 2010, 31, 123–129. <https://doi.org/10.1055/s-0029-1242815>.
- Sauvé, B.; Haugan, M.; Paulsen, G. Physical and Physiological Characteristics of Elite CrossFit Athletes. *Sports* 2024, 12, 162. <https://doi.org/10.3390/sports12060162>.
- Senefeld, J.; Hunter, S. Hormonal Basis of Biological Sex Differences in Human Athletic Performance. *Endocrinology* 2024, 165, bqae036. <https://doi.org/10.1210/endo/bqae036>.
- Tan, K.L.; Chung, H.J. Injury Causes and Recovery Management Strategies among Singapore CrossFitters. *ACPEJ. Phys. Educ. Sport Health (AJPESH)* 2021, 1, 134–144. <https://doi.org/10.15294/ajpesh.v1i2.52589>.
- Tibana, R.; Neto, I.; Sousa, N.; Romeiro, C.; Hanai, A.; Brandão, H.; Dominski, F.H.; Voltarelli, F. Local Muscle Endurance and Strength Had Strong Relationship with CrossFit Open 2020 in Amateur Athletes. *Sports* 2021, 9, 98. <https://doi.org/10.3390/sports9070098>.
- Toledo, R.; Dias, M.; Toledo, R.; Erotides, R.; Pinto, D.; Reis, V.; Novaes, J.S.; Vianna, J.M.; Heinrich, K. Comparison of Physiological Responses and Training Load between Different CrossFit Workouts with Equalized Volume in Men and Women. *Life* 2021, 11, 586. <https://doi.org/10.20944/preprints202105.0733.v1>.
- Young, M. The Use of a Jump Test to Assess Leg Power in Athletes. *Strength Cond. J.* 1995, 17, 18–21.
- Zhang, W.; Cui, Z.; Shen, D.; Li, G.; Li, Q. Testosterone Levels Positively Linked to Muscle Mass but Not Strength in Adult Males Aged 20–59 Years: A Cross-Sectional Study. *Front. Physiol.* 2025, 16, 1512268. <https://doi.org/10.3389/fphys.2025.1512268>.

Chapter 3. Study 3

- Aravena-Sagardia, P.; Barramuño-Medina, M.; Vásquez, B.P.; Pichinao, S.; Sepúlveda, P.R.; Herrera-Valenzuela, T.; Hernandez-Martinez, J.; Levín-Catrilao, Á.; Villagrán-Silva, F.; Vásquez-Carrasco, E.; et al. Effects of a CrossFit Training Program on Body Composition and Physical Fitness in Novice and Advanced Practitioners: An Inter-Individual Analysis. *Appl. Sci.* 2025, 15, 3554. <https://doi.org/10.3390/app15073554>.
- Archacki, D.; Zieliński, J.; Ciekot-Sołtysiak, M.; Zarębska, E.; Kusy, K. Sex Differences in the Energy System Contribution during Sprint Exercise in Speed-Power and Endurance Athletes. *J. Clin. Med.* 2024, 13, 4812. <https://doi.org/10.3390/jcm13164812>
- Bagchi, A.; Raizada, S.; Thapa, R.K.; Ștefănică, V.; Ceylan, H.İ. Reliability and Accuracy of Portable Devices for Measuring Countermovement Jump Height in Physically Active Adults: A Comparison of Force Platforms, Contact Mats, and Video-Based Software. *Life* 2024, 14, 1423. <https://doi.org/10.3390/life14111423>
- Becher, H. The Concept of Residual Confounding in Regression Models and Some Applications. *Stat. Med.* 1992, 11, 1747–1758. <https://doi.org/10.1002/sim.4780111308>
- Bellar, D.; Hatchett, A.; Judge, L.; Breaux, M.; Marcus, L. The Relationship of Aerobic Capacity, Anaerobic Peak Power and Experience to Performance in HIT Exercise. *Biol. Sport* 2015, 32, 315–320. <https://doi.org/10.5604/20831862.1174771>
- Blair, M.L. Sex-Based Differences in Physiology: What Should We Teach in the Medical Curriculum? *Adv. Physiol. Educ.* 2007, 31, 23–25. <https://doi.org/10.1152/advan.00118.2006>.
- Breitbach, S.; Sterzing, B.; Magallanes, C.; Tug, S.; Simon, P. Direct Measurement of Cell-Free DNA from Serially Collected Capillary Plasma during Incremental Exercise. *J. Appl. Physiol.* 2014, 117, 119–130. <https://doi.org/10.1152/jappphysiol.00002.2014>
- Camacho-Cardenosa, A.; Timón, R.; Camacho-Cardenosa, M.; Guerrero-Flores, S.; Olcina, G.; Marcos-Serrano, M. Six-Months CrossFit Training Improves Metabolic Efficiency in Young Trained Men. *Cult. Cienc. Deporte* 2020, 15, 421–427. <https://doi.org/10.12800/ccd.v15i45.1519>
- Cesanelli, L.; Eimantas, N.; Iovane, A.; Messina, G.; Satkunskienė, D. The Role of Age on Neuromuscular Performance Decay Induced by a Maximal Intensity Sprint Session in a Group of Competitive Endurance Athletes. *Eur. J. Transl. Myol.* 2022, 32, 10378. <https://doi.org/10.4081/ejtm.2022.10378>

- Claudino, J.G.; Gabbett, T.J.; Bourgeois, F.; Souza, H.S.; Miranda, R.C.; Mezêncio, B.; Serrão, J.C. CrossFit Overview: Systematic Review and Meta-Analysis. *Sports Med. Open* 2018, 4, 11. <https://doi.org/10.1186/s40798-018-0124-5>
- Coco, M.; Corrado, D.D.; Cirillo, F.; Iacono, C.; Perciavalle, V.; Buscemi, A. Effects of General Fatigue Induced by Exhaustive Exercise on Posture and Gait Stability of Healthy Young Men. *Behav. Sci.* 2021, 11, 72. <https://doi.org/10.3390/bs11050072>
- Cohen, J. *Statistical Power Analysis for the Behavioral Sciences*, 2nd ed.; Lawrence Erlbaum Associates: Hillsdale, NJ, USA, 1988.
- Cormie, P.; McGuigan, M.R.; Newton, R.U. Developing Maximal Neuromuscular Power: Part 2—Training Considerations for Improving Maximal Power Production. *Sports Med.* 2011, 41, 125–146. <https://doi.org/10.2165/11538500-000000000-00000>
- Cruz-Díaz, D.; Hita-Contreras, F.; Martínez-Amat, A.; Aibar-Almazán, A.; Kim, K. Ankle-Joint Self-Mobilization and CrossFit Training in Patients with Chronic Ankle Instability: A Randomized Controlled Trial. *J. Athl. Train.* 2020, 55, 159–168. <https://doi.org/10.4085/1062-6050-181-18>
- D’Hulst, G.; Hodžić, D.; Leuenberger, R.; Arnet, J.; Westerhuis, E.; Roth, R.; Schmidt-Trucksäss, A.; Knaier, R.; Wagner, J. Physiological Profiles of Male and Female CrossFit Athletes. *Int. J. Sports Physiol. Perform.* 2024, 19, 780–791. <https://doi.org/10.1123/ijsp.2023-0386>
- DeBlauw, J.; Drake, N.; Kurtz, B.; Crawford, D.; Carper, M.; Wakeman, A.; Heinrich, K. High-Intensity Functional Training Guided by Individualized Heart Rate Variability Results in Similar Health and Fitness Improvements as Predetermined Training with Less Effort. *J. Funct. Morphol. Kinesiol.* 2021, 6, 102. <https://doi.org/10.3390/jfmk6040102>
- Dexheimer, J.D.; Schroeder, E.T.; Sawyer, B.J.; Pettitt, R.W.; Aguinaldo, A.L.; Torrence, W.A. Physiological Performance Measures as Indicators of CrossFit® Performance. *Sports* 2019, 7, 93. <https://doi.org/10.3390/sports7040093>
- Díaz, J.J.; Fernández-Ozcorta, E.J.; Torres, M.; Santos-Concejero, J. Men vs. Women World Marathon Records’ Pacing Strategies from 1998 to 2018. *Eur. J. Sport Sci.* 2019, 19, 1297–1302. <https://doi.org/10.1080/17461391.2019.1596165>
- Dominski, F.; Serafim, T.; Siqueira, T.; Andrade, A. Psychological Variables of CrossFit Participants: A Systematic Review. *Sport Sci. Health* 2021, 17, 21–41. <https://doi.org/10.1007/s11332-020-00685-9>
- Édouard, P.; Feddermann-Demont, N.; Alonso, J.; Branco, P.; Junge, A. Injury Risk Is Different between Male and Female Athletes during 14 International Athletics Championships. *Br. J. Sports Med.* 2017, 51, 315. <https://doi.org/10.1136/bjsports-2016-097372.81>

- Edwards, T.; Weakley, J.; Woods, C.T.; Breed, R.; Benson, A.; Suchomel, T.J.; Banyard, H.G. Comparison of Countermovement Jump and Squat Jump Performance between State and Non-State Representative Junior Australian Football Players. *J. Strength Cond. Res.* 2023, *37*, 641–645. <https://doi.org/10.1519/JSC.0000000000004299>
- Ferraz, A.; Alonso, E.; Ribeiro, J.N.; Spyrou, K.; Freitas, T.T.; Valente-dos-Santos, J.; Travassos, B. Bridging the Gap between Training and Competition in Elite Rink Hockey: A Pilot Study. *Sports Health* 2025, *17*, 57–65. <https://doi.org/10.1177/19417381241273219>
- Fernández, J.F.; Solana, R.S.; Moya, D.; Marin, J.M.; Sáez de Villarreal, E. Acute Physiological Responses during CrossFit® Workouts. *Eur. J. Hum. Mov.* 2015, *35*, 114–124. Available online: <https://www.eurjhm.com/index.php/eurjhm/article/view/362> (accessed on 14 September 2025).
- Fiorenza, M.; Lemminger, A.; Marker, M.; Eibye, K.; Iaia, F.; Bangsbo, J.; Hostrup, M. High-Intensity Exercise Training Enhances Mitochondrial Oxidative Phosphorylation Efficiency in a Temperature-Dependent Manner in Human Skeletal Muscle. *FASEB J.* 2019, *33*, 8976–8989. <https://doi.org/10.1096/fj.201900106RRR>
- Forte, L.D.M.; Freire, Y.G.C.; Júnior, J.S.S.; Melo, D.A.; Meireles, C.L.S. Physiological Responses after Two Different CrossFit Workouts. *Biol. Sport* 2022, *39*, 231–236. <https://doi.org/10.5114/biolsport.2021.102928>
- Forte, P.; Encarnação, S.G.; Teixeira, J.E.; Branquinho, L.; Barbosa, T.M.; Monteiro, A.M.; Pecos-Martín, D. Predicting Sleep Quality Based on Metabolic, Body Composition, and Physical Fitness Variables in Aged People. *J. Funct. Morphol. Kinesiol.* 2025, *10*, 337. <https://doi.org/10.3390/jfmk10030337>
- González-Badillo, J.J.; Marques, M.C.; Sánchez-Medina, L. The Importance of Movement Velocity as a Measure to Control Resistance Training Intensity. *J. Hum. Kinet.* 2011, *29*, 15–19. <https://doi.org/10.2478/v10078-011-0053-6>
- Higgins, T.R.; Lloyd, T.; Manalansan, K.; McDonald, S.; Thomas, B. Comparisons in Heart Rate Readings between the Bioconnected Wireless Exercise Earpiece and a Polar T31-Coded Chest Strap during a GXT. *J. Hum. Sport Exerc.* 2018, *13*, 3. <https://doi.org/10.14198/jhse.2018.133.05>
- Howards, P.P. An Overview of Confounding. Part 1: The Concept and How to Address It. *Acta Obstet. Gynecol. Scand.* 2018, *97*, 394–399. <https://doi.org/10.1111/aogs.13295>

- Hung, C.-H.; Su, C.-H.; Wang, D. The Role of High-Intensity Interval Training (HIIT) in Neuromuscular Adaptations: Implications for Strength and Power Development—A Review. *Life* 2025, *15*, 657. <https://doi.org/10.3390/life15040657>
- Hunter, S.; Angadi, S.; Bhargava, A.; Harper, J.; Hirschberg, A.; Levine, B.; Bermon, S. The Biological Basis of Sex Differences in Athletic Performance: Consensus Statement for the American College of Sports Medicine. *Med. Sci. Sports Exerc.* 2023, *55*, 2328–2360. <https://doi.org/10.1249/MSS.0000000000003300>
- Jacob, M.; Keiner, M.; Holmberg, H.C.; Häkkinen, K. Physiological Responses to CrossFit® Training: A Systematic Review. *Front. Physiol.* 2020, *11*, 1001. <https://doi.org/10.3389/fphys.2020.01001>
- Kaufman, M.; Nguyen, C.; Shetty, M.; Opezzo, M.; Barrack, M.; Fredericson, M. Popular Dietary Trends' Impact on Athletic Performance: A Critical Analysis Review. *Nutrients* 2023, *15*, 3511. <https://doi.org/10.3390/nu15163511>
- Kozinc, Ž.; Pleša, J.; Šarabon, N. Questionable Utility of the Eccentric Utilization Ratio in Relation to the Performance of Volleyball Players. *Int. J. Environ. Res. Public Health* 2021, *18*, 11754. <https://doi.org/10.3390/ijerph182211754>.
- Lambrick, D.; Rowlands, A.V.; Rowland, T.; Eston, R. Pacing Strategies of Inexperienced Children during Repeated 800 m Individual Time-Trials and Simulated Competition. *Pediatr. Exerc. Sci.* 2013, *25*, 198–211. <https://doi.org/10.1123/pes.25.2.198>
- Langford, E.L.; Bergstrom, H.C.; Lanham, S.; Eastman, A.Q.; Best, S.; Ma, X.; Abel, M.G. Evaluation of Work Efficiency in Structural Firefighters. *J. Strength Cond. Res.* 2023, *37*, 2457–2466. <https://doi.org/10.1519/JSC.0000000000004577>
- Leitão, L.; Dias, M.R.; Campos, Y.; Vieira, J.G.; Sant'Ana, L.O.; Telles, L.G.S.; Vianna, J.M. Physical and Physiological Predictors of Fran CrossFit WOD Athlete's Performance. *Int. J. Environ. Res. Public Health* 2021, *18*, 4070. <https://doi.org/10.3390/ijerph18084070>
- Lindmark, A.; de Luna, X.; Eriksson, M. Sensitivity Analysis for Unobserved Confounding of Direct and Indirect Effects Using Uncertainty Intervals. *Stat. Med.* 2018, *37*, 1744–1762. <https://doi.org/10.1002/sim.7620>
- Mangine, G.; Tankersley, J.; McDougale, J.; Velazquez, N.; Roberts, M.; Esmat, T.; Feito, Y. Predictors of CrossFit Open Performance. *Sports* 2020, *8*, 102. <https://doi.org/10.3390/sports8070102>
- Mangine, G.T.; McDougale, J.M. CrossFit Open Performance Is Affected by the Nature of Past Competition Experiences. *BMC Sports Sci. Med. Rehabil.* 2022, *14*, 46. <https://doi.org/10.1186/s13102-022-00434-0>

- Marzano-Felisatti, J.M.; Lucca, L.D.; Luján, J.F.G.; Priego-Quesada, J.I.; Pino-Ortega, J. A Preliminary Investigation about the Influence of WIMU Pro™ Location on Heart Rate Accuracy: A Comparative Study in Cycle Ergometer. *Sensors* 2024, *24*, 988. <https://doi.org/10.3390/s24030988>
- Martínez-Gómez, R.; Valenzuela, L.P.; Barranco-Gil, D.; Moral-González, S.; García-González, A.; Lucia, A. Full-Squat as a Determinant of Performance in CrossFit. *Int. J. Sports Med.* 2019, *40*, 592–596. <https://doi.org/10.1055/a-0852-5565>
- Martínez-Gómez, R.; Valenzuela, P.; Alejo, L.; Gil-Cabrera, J.; Montalvo-Pérez, A.; Talavera, E.; Barranco-Gil, D. Physiological Predictors of Competition Performance in CrossFit Athletes. *Int. J. Environ. Res. Public Health* 2020, *17*, 3699. <https://doi.org/10.3390/ijerph17103699>
- Maté-Muñoz, J.L.; Maicas-Pérez, L.; Aparicio-García, I.; Hernández-Lougedo, J.; Sousa, L.S.; Hontoria-Galán, M.; Elvar, J.R.H. Are Perceived Effort Scales (OMNI-RES) Appropriate for Defining and Controlling Strength Training Intensity? *Sports* 2025, *13*, 57. <https://doi.org/10.3390/sports13020057>
- McLaren, S.J.; Graham, M.; Spears, I.R.; Weston, M. The Sensitivity of Differential Ratings of Perceived Exertion as Measures of Internal Load. *Int. J. Sports Physiol. Perform.* 2016, *11*, 404–406. <https://doi.org/10.1123/ijsp.2015-0223>
- Meier, N.; Schlie, J.; Schmidt, A. CrossFit: ‘Unknowable’ or Predictable?—A Systematic Review on Predictors of CrossFit Performance. *Sports* 2023, *11*, 112. <https://doi.org/10.3390/sports11060112>
- Menting, S.; Edwards, A.; Hettinga, F.; Elferink-Gemser, M. Pacing Behaviour Development and Acquisition: A Systematic Review. *Sports Med. Open* 2022, *8*, 117. <https://doi.org/10.1186/s40798-022-00540-w>
- Micklewright, D.; Papadopoulou, E.; Swart, J.; Noakes, T.D. Previous Experience Influences Pacing during 20 km Time Trial Cycling. *Br. J. Sports Med.* 2010, *44*, 952–960. <https://doi.org/10.1136/bjism.2009.057315>
- Myer, G.D.; Ford, K.R.; McLean, S.; Hewett, T.E. The Effects of Plyometric versus Dynamic Stabilization and Balance Training on Lower Extremity Biomechanics. *Am. J. Sports Med.* 2006, *34*, 445–455. <https://doi.org/10.1177/0363546505281241>
- Panoutsakopoulos, V.; Kotzamanidou, M.C.; Papaiakevou, G.; Kollias, I. The Ankle Joint Range of Motion and Its Effect on Squat Jump Performance with and without Arm Swing in Adolescent Female Volleyball Players. *J. Funct. Morphol. Kinesiol.* 2021, *6*, 14. <https://doi.org/10.3390/jfmk6010014>
- Petrigna, L.; Karsten, B.; Marcolin, G.; Paoli, A.; D’Antona, G.; Palma, A.; Bianco, A. A Review of Countermovement and Squat Jump Testing Methods in the Context of

- Public Health Examination in Adolescence. *Front. Physiol.* 2019, 10, 1384. <https://doi.org/10.3389/fphys.2019.01384>
- Piero, D.W.; Esteve, T.V.; Castán, J.C.R.; Abella, C.P.; Díaz-Pintado, J.V.S. Effects of Work-Interval Duration and Sport Specificity on Blood Lactate Concentration, Heart Rate and Perceptual Responses during High Intensity Interval Training. *PLoS ONE* 2018, 13, e0200690. <https://doi.org/10.1371/journal.pone.0200690>
- Ponce-García, T.; García-Romero, J.; Carrasco-Fernández, L.; Castillo-Domínguez, A.; Benítez-Porres, J. The Association of Whole and Segmental Body Composition and Anaerobic Performance in CrossFit Athletes. *Retos* 2024, 62, 186–194. <https://doi.org/10.47197/retos.v62.113599>
- Ponce-García, T.; García-Romero, J.; Carrasco-Fernandez, L.; Castillo-Domínguez, A.; Benítez-Porres, J. Sex Differences in Anaerobic Performance in CrossFit® Athletes: A Comparison of Three Different All-Out Tests. *PeerJ* 2025, 13, e18930. <https://doi.org/10.7717/peerj.18930>
- Pryor, J.L.; Johnson, E.C.; Yoder, H.A.; Looney, D.P. Keeping Pace: A Practitioner-Focused Review of Pacing Strategies in Running. *Strength Cond. J.* 2020, 42, 67–75. <https://doi.org/10.1519/SSC.0000000000000505>
- Pueo, B.; Penichet-Tomás, A.; Jiménez-Olmedo, J.M. Reliability and Validity of the Chronojump Open-Source Jump Mat System. *Biol. Sport* 2020, 37, 255–259. <https://doi.org/10.5114/biol sport.2020.95636>
- Qiu, S.; Alzhab, S.; Picard, G.; Taylor, J.A. Ventilation Limits Aerobic Capacity after Functional Electrical Stimulation Row Training in High Spinal Cord Injury. *Med. Sci. Sports Exerc.* 2016, 48, 1111–1118. <https://doi.org/10.1249/MSS.0000000000000880>
- Rios, M.; Becker, K.M.; Monteiro, A.S.; Fonseca, P.; Pyne, D.B.; Reis, V.M.; Fernandes, R.J. Effect of the Fran CrossFit Workout on Oxygen Uptake Kinetics, Energetics, and Postexercise Muscle Function in Trained CrossFitters. *Int. J. Sports Physiol. Perform.* 2024, 19, 299–306. <https://doi.org/10.1123/ijsp.2023-0201>
- Rios, M.; Cardoso, R.; Reis, M.R.; Moreira-Gonçalves, D.; Pyne, B.D.; Fernandes, J.R. Sex-Related Differences in the Acute Physiological Response to a High-Intensity CrossFit Workout. *Physiology* 2025, 8, 100148. <https://doi.org/10.1016/j.crphys.2025.100148>
- Rodrigues, A.; Resende, R.; Pogetti, L.; Santos, T.; Faria, H.; Chagas, M.; Ocarino, J. Trunk, Mass Grasp, Knee, and Hip Muscle Performance in CrossFit Participants. *Int. J. Sports Phys. Ther.* 2023, 18, 726–736. <https://doi.org/10.26603/001c.75222>

- Sandbakk, S.; Tønnessen, E.; Haugen, T.; Sandbakk, Ø. Training and Coaching of Female vs. Male Endurance Athletes on Their Road to Gold. *Ger. J. Exerc. Sport Res.* 2022, 73, 251–258. <https://doi.org/10.5960/dzsm.2022.549>
- Sands, W.A.; Bogdanis, G.C.; Penitente, G.; Donti, O.; McNeal, J.R.; Butterfield, C.C.; Barker, L. Reliability and Validity of a Low-Cost Portable Force Platform. *Isokinet. Exerc. Sci.* 2020, 28, 247–253. <https://doi.org/10.3233/IES-202106>
- Sanfilippo, J.; Krueger, D.; Heiderscheidt, B.C.; Binkley, N. Dual-Energy X-ray Absorptiometry Body Composition in NCAA Division I Athletes. *Sports Health* 2019, 11, 453–460. <https://doi.org/10.1177/1941738119861572>
- Schisterman, E.F.; Cole, S.R.; Platt, R.W. The Role of Measurement Error in the Evaluation of Causal Effects. *Am. J. Epidemiol.* 2009, 170, 962–970. <https://doi.org/10.1093/aje/kwp253>
- Schlegel, P.; Křehký, A. Performance Sex Differences in CrossFit®. *Sports* 2022, 10, 165. <https://doi.org/10.3390/sports10110165>
- Senefeld, J.; Hunter, S. Hormonal Basis of Biological Sex Differences in Human Athletic Performance. *Endocrinology* 2024, 165, bqae036. <https://doi.org/10.1210/endocr/bqae036>
- Smajla, D.; Vlahović, T.; Rupčić, T.; Pocek, S.; Baić, M. Reliability of an Inertial Sensor Device for Jump Performance Assessment in Collegiate Athletes. *Life* 2024, 14, 1394. <https://doi.org/10.3390/life14111394>
- Szklo, M.; Nieto, F.J. *Epidemiology: Beyond the Basics*, 3rd ed.; Jones & Bartlett Learning: Burlington, MA, USA, 2014.
- Tibana, R.; Neto, I.; Sousa, N.; Romeiro, C.; Hanai, A.; Brandão, H.; Voltarelli, F. Local Muscle Endurance and Strength Had Strong Relationship with CrossFit Open 2020 in Amateur Athletes. *Sports* 2021, 9, 98. <https://doi.org/10.3390/sports9070098>
- Toledo, R.; Dias, M.; Toledo, R.; Erotides, R.; Pinto, D.; Reis, V.; Heinrich, K. Comparison of Physiological Responses and Training Load between Different CrossFit Workouts. *Life* 2021, 11, 586. <https://doi.org/10.3390/life11060586>
- Tucker, M.A.; Lee, N.; Rodriguez-Miguel, P.; Looney, J.; Crandall, R.; Forseen, C.; Harris, R.A. Exercise Testing in Patients with Cystic Fibrosis—Importance of Ventilatory Parameters. *Eur. J. Appl. Physiol.* 2019, 119, 227–234. <https://doi.org/10.1007/s00421-018-4018-5>
- Weiss, E.P.; Spina, R.J.; Holloszy, J.O.; Ehsani, A.A. Gender Differences in the Decline in Aerobic Capacity and Its Physiological Determinants during the Later Decades of Life. *J. Appl. Physiol.* 2006, 101, 938–944. <https://doi.org/10.1152/jappphysiol.01398.2005>

- Woo, J.; Derleth, C.L.; Stratton, J.R.; Levy, W.C. The Influence of Age, Gender, and Training on Exercise Efficiency. *J. Am. Coll. Cardiol.* 2006, *47*, 1049–1057. <https://doi.org/10.1016/j.jacc.2005.09.066>
- Zeitz, E.; Cook, L.; Dexheimer, J.D.; Lemez, S.; Leyva, W.D.; Terbio, I.Y.; Jo, E. The Relationship between CrossFit Performance and Laboratory-Based Measurements of Fitness. *Sports* 2020, *8*, 112. <https://doi.org/10.3390/sports8080112>
- Zhang, W.; Cui, Z.; Shen, D.; Li, G.; Li, Q. Testosterone Levels Positively Linked to Muscle Mass but Not Strength in Adult Males Aged 20–59 Years. *Front. Physiol.* 2025, *16*, 1512268. <https://doi.org/10.3389/fphys.2025.1512268>
- Zhao, Q.; Adeli, E.; Pohl, K.M. Training Confounder-Free Deep Learning Models for Medical Applications. *Nat. Commun.* 2020, *11*, 6010. <https://doi.org/10.1038/s41467-020-19784-9>

Chapter 4. General Discussion

- Bellar, D., Hatchett, A., Judge, L. W., Breaux, M. E., & Marcus, L. (2015). The relationship of aerobic capacity, anaerobic peak power and experience to performance in CrossFit exercise. *Biology of Sport*, *32*(4), 315–320. <https://doi.org/10.5604/20831862.1163699>
- Bishop, D., Girard, O., & Mendez-Villanueva, A. (2011). Repeated-sprint ability—Part II: Recommendations for training. *Sports Medicine*, *41*(9), 741–756. <https://doi.org/10.2165/11590560-000000000-00000>
- Bouchard, C., & Rankinen, T. (2001). Individual differences in response to regular physical activity. *Medicine & Science in Sports & Exercise*, *33*(6 Suppl), S446–S451. <https://doi.org/10.1097/00005768-200106001-00013>
- Buckley, S., Knapp, K., Lackie, A., Lewry, C., Horvey, K., Benko, C., Trinh, J., & Butcher, S. (2015). Multimodal high-intensity interval training increases muscle function and metabolic performance in females. *Applied Physiology, Nutrition, and Metabolism*, *40*(11), 1157–1162. <https://doi.org/10.1139/apnm-2015-0238>
- Butcher, S. J., Neyedly, T. J., Horvey, K. J., & Benko, C. R. (2015). Do physiological measures predict selected CrossFit® benchmark performance? *Open Access Journal of Sports Medicine*, *6*, 241–247. <https://doi.org/10.2147/OAJSM.S88265>
- Claudino, J. G., Gabbett, T. J., Bourgeois, F., de Sá Souza, H., Miranda, R. C., Mezêncio, B., Soncin, R., et al. (2018). CrossFit overview: Systematic review and meta-analysis. *Sports Medicine - Open*, *4*(1), 11. <https://doi.org/10.1186/s40798-018-0124-5>
- Dexheimer, J. D., Schroeder, E. T., Sawyer, B. J., Pettitt, R. W., Aguinaldo, A. L., & Torrence, W. A. (2019). Physiological performance measures as predictors of

- CrossFit Open performance. *Sports*, 7(5), 93. <https://doi.org/10.3390/sports7050093>
- Dominski, F. H., Matias, T. S., Serafim, T. T., Andrade, A., & et al. (2021). Physical and physiological demands of CrossFit: A systematic review. *Sports Medicine - Open*, 7(1), 8. <https://doi.org/10.1186/s40798-020-00283-0>
- Drum, S. N., Bellovary, B. N., Jensen, R. L., Moore, M. T., & Donath, L. (2017). Perceived demands and post-exercise physical dysfunction in CrossFit® practitioners. *Journal of Sports Medicine and Physical Fitness*, 57(12), 1539–1546. <https://doi.org/10.23736/S0022-4707.16.06771-2>
- González, A. M., Mangine, G. T., Fragala, M. S., Stout, J. R., Beyer, K. S., Bohner, J. D., & Hoffman, J. R. (2017). Resistance training adaptations in trained and untrained men. *Journal of Strength and Conditioning Research*, 31(2), 497–503. <https://doi.org/10.1519/JSC.0000000000001525>
- González-Badillo, J. J., & Sánchez-Medina, L. (2010). Movement velocity as a measure of loading intensity in resistance training. *International Journal of Sports Medicine*, 31(5), 347–352. <https://doi.org/10.1055/s-0030-1248333>
- Hopkins, W. G. (2000). Measures of reliability in sports medicine and science. *Sports Medicine*, 30(1), 1–15. <https://doi.org/10.2165/00007256-200030010-00006>
- Mangine, G. T., Stratton, M. T., Almeda, C. G., Roberts, M. D., Esmat, T. A., VanDusseldorp, T. A., & Feito, Y. (2020). Physiological predictors of competition performance in CrossFit athletes. *Sports*, 8(7), 111. <https://doi.org/10.3390/sports8070111>
- Martínez-Gómez, R., Valenzuela, P. L., Barranco-Gil, D., García-Fernández, P., Sánchez-Moreno, M., & Lucia, A. (2019). Physiological predictors of performance in the “CrossFit Open.” *Journal of Sports Sciences*, 37(16), 1905–1913. <https://doi.org/10.1080/02640414.2019.1609897>
- Meier, T., Antunes, B. M., Dalleck, L. C., & Tibana, R. A. (2023). Biomechanical and physiological demands of CrossFit: A systematic review. *Journal of Functional Morphology and Kinesiology*, 8(1), 5. <https://doi.org/10.3390/jfmk8010005>
- Sandbakk, Ø., & Holmberg, H. C. (2017). Physiological capacity and training routines of elite cross-country skiers: Approaching the upper limits of human endurance. *International Journal of Sports Physiology and Performance*, 12(8), 1003–1011. <https://doi.org/10.1123/ijspp.2016-0749>
- Schlegel, P., & Křehký, A. (2022). Sex differences in CrossFit performance: Evidence from large-scale competition. *Frontiers in Physiology*, 13, 820593. <https://doi.org/10.3389/fphys.2022.820593>

- Thompson, W. R. (2020). Worldwide survey of fitness trends for 2020. *ACSM's Health & Fitness Journal*, 24(6), 10–18. <https://doi.org/10.1249/FIT.0000000000000526>
- Tibana, R. A., & de Sousa, N. M. F. (2018). Are extreme conditioning programs effective and safe? A narrative review of high-intensity functional training. *Frontiers in Physiology*, 9, 1216. <https://doi.org/10.3389/fphys.2018.01216>
- Tibana, R. A., de Sousa, N. M. F., Prestes, J., Nascimento, D. C., et al. (2018). Time-course of physiological and metabolic responses to CrossFit® WODs. *Biology of Sport*, 35(3), 239–246. <https://doi.org/10.5114/biolsport.2018.78058>
- Zeitz, J., Kilian, Y., & et al. (2020). Predictors of performance in CrossFit athletes: A systematic review. *Journal of Human Kinetics*, 75(1), 37–48. <https://doi.org/10.2478/hukin-2020-0045>



Appendix

Table 1. Strength and mechanical performance during resistance exercises at 80% of 1RM, compared by sex.

	Pooled	Males (n = 8)	Females (n = 7)	Δ%
1RM BS (kg)	104.6 ± 28.4	124.1 ± 24.2	82.4 ± 10.5	16.6
Vmax (m/s) (80%) 1RM BS	1.0 ± 0.1	0.9 ± 0.1	1.0 ± 0.1	-7.6
V (m/s) (80%) 1RM BS	0.5 ± 0.1	0.5 ± 0.1	0.5 ± 0.1	-1.9
Power (W) (80%) 1RM BS	823.8 ± 203.2	960.2 ± 182.9	668.0 ± 64.9	13.1
Max Power (W) (80%) 1RM BS	1822.4 ± 412.8	2065.8 ± 374.0	1544.3 ± 255.4	5.9
Force (N) (80%) 1RM BS	1585.2 ± 337.0	1838.1 ± 224.8	1296.0 ± 152.4	14.1
Max Force (N) (80%) 1RM BS	2033.2 ± 462.8	2340.1 ± 390.9	1682.5 ± 228.7	16.4
1RM DL (kg)	134.9 ± 30.3	155.4 ± 27.9	111.7 ± 6.3	15.8
Vmax (m/s) (80%) 1RM DL	0.8 ± 0.1	0.9 ± 0.1	0.8 ± 0.1	-11.1
V(m/s) (80%) 1RM DL	0.6 ± 0.0	0.6 ± 0.0	0.5 ± 0.0	1.9
Power (W) (80%) 1RM DL	562.1 ± 150.2	641.9 ± 120.1	470.9 ± 132.6	18.0
Max Power (W) (80%) 1RM DL	951.5 ± 222.6	1084.0 ± 186.8	799.9 ± 157.1	11.1
Force (N) (80%) 1RM DL	1051.8 ± 277.2	1198.4 ± 202.3	884.2 ± 264.9	20.5
Max Force (N) (80%) 1RM DL	1291.5 ± 348.5	1466.5 ± 262.2	1091.4 ± 340.0	18.5
1RM BP (kg)	69.4 ± 25.5	88.9 ± 17.7	47.1 ± 7.9	21.8
Vmax (m/s) (80%) 1RM BP	0.7 ± 0.1	0.7 ± 0.1	0.7 ± 0.1	-9.5
V(m/s) (80%) 1RM BP	0.5 ± 0.1	0.5 ± 0.1	0.5 ± 0.0	-1.9
Power (W) (80%) 1RM BP	293.7 ± 117.5	349.7 ± 79.0	229.7 ± 126.4	34.3
Max Power (W) (80%) 1RM BP	452.7 ± 187.9	529.6 ± 125.9	364.8 ± 216.9	29.5
Force (N) (80%) 1RM BP	557.3 ± 219.5	680.2 ± 130.9	416.9 ± 222.1	28.8
Max Force (N) (80%) 1RM BP	787.9 ± 343.2	936.2 ± 205.7	618.6 ± 403.3	35.6

1RM: one-repetition maximum; BP: bench press; BS: back squat ; DL: deadlift; V: velocity.