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Special Issue Reprint

Benefits of Physical Activity and Exercise to Human Health

Edited by
Ricardo Manuel Pires Ferraz, Henrique P. Neiva, Fernanda M. Silva
and Pedro Alexandre Duarte-Mendes

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Guest Editors

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This is a reprint of the Special Issue, published open access by the journal *Sports* (ISSN 2075-4663), freely accessible at: https://www.mdpi.com/journal/sports/special_issues/ZV74P0608T.

For citation purposes, cite each article independently as indicated on the article page online and as indicated below:

Lastname, A.A.; Lastname, B.B. Article Title. *Journal Name* **Year**, *Volume Number*, Page Range.

ISBN 978-3-7258-8781-1 (Hbk)
ISBN 978-3-7258-8782-8 (PDF)
https://doi.org/10.3390/books978-3-7258-8782-8

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About the Editors

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Ricardo Manuel Pires Ferraz is an Associate Professor at the University of Beira Interior (UBI), Covilhã, Portugal. He is an integrated researcher at the Research Center in Sports Sciences, Health Sciences and Human Development (CIDESD). He serves on the editorial boards of several international journals, both as Associate Editor and Guest Editor, with a particular focus on sport sciences, exercise, and physical education. His current research is primarily centred on football performance, training load monitoring and physical performance in team sports. He has also developed a sustained research line in Physical Education, addressing instructional approaches, pedagogical models, and the promotion of physically active lifestyles in educational contexts. Aside from authoring numerous peer-reviewed publications in the sport sciences literature, he has supervised several doctoral and master's students and has been actively involved in research projects, international scientific collaboration, and academic leadership.

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Preface

Physical activity and exercise are central components of health promotion and disease prevention across the lifespan. This Reprint was prepared to bring together scientific contributions that explore their role in improving physical, cognitive, mental, and functional health in different populations and settings. The aim is to provide researchers, health professionals, exercise specialists, educators, and policy makers with current evidence on how movement-based strategies can support healthier lives. The works included in this Reprint encompass children, adolescents, adults, older adults, and clinical populations, offering perspectives on prevention, rehabilitation, performance, well-being, and quality of life. We hope that this Reprint will contribute to the development of safe, effective, and context-specific approaches to promoting physical activity and exercise in both research and practice.

Ricardo Manuel Pires Ferraz, Henrique P. Neiva, Fernanda M. Silva, and Pedro Alexandre Duarte-Mendes

Guest Editors

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Editorial

Editorial for the 1st Edition Special Issue "Benefits of Physical Activity and Exercise to Human Health"

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1. Introduction

Recent estimates indicate that the prevalence of insufficient physical activity has been increasing globally, with nearly one third of adults (31.3%) [1] and eight in ten adolescents (81%) [2] not meeting the World Health Organization physical activity guidelines (i.e., 150–300 min per week of moderate-to-vigorous intensity aerobic physical activity for adults and 60 min per day for children and adolescents [3]). According to authors [1,2], if the current trajectory continues, the global target of a 15% relative reduction in insufficient physical activity by 2030 [4] is unlikely to be achieved in most countries. This data are concerning given that, globally, 7.2% of all-cause deaths and 7.6% of cardiovascular disease deaths are attributable to physical inactivity [5].

Physical activity and exercise are widely recognized for promoting numerous health benefits, particularly in the prevention and management of obesity and cardiometabolic diseases [6,7], as well as in supporting immune function, reducing the risk of infectious diseases, improving mental health, and contributing to cancer prevention and control [8]. Moreover, regular engagement in these behaviors is associated with a reduced risk of all-cause mortality [9]. From a public health perspective, developing and implementing evidence-based strategies to increase physical activity and improve population health remains a global priority [8].

In this context, this Special Issue aims to advance knowledge on the role of physical activity and exercise interventions in promoting health and well-being across the lifespan. The contributions examine the effects of different exercise modalities on physical, cognitive, and mental health, as well as the role of physical activity in disease prevention and management and in improving functional capacity and quality of life across diverse populations. Collectively, the twelve papers included in this Special Issue provide complementary perspectives on these topics.

2. An Overview of Published Articles

Some studies in this Special Issue highlight the physiological and cognitive benefits of exercise interventions. The study by Nakao et al. (contribution 1) presents a randomized

crossover trial examining the combined effects of aerobic training performed under mild hyperbaric oxygen (HBO) or normobaric normoxia (NN) environments, with concurrent eicosapentaenoic acid supplementation, on processing efficiency and interference indices in Stroop-type cognitive tasks among young men. The results showed improvements over time in processing efficiency following the training program, irrespective of the environmental condition. However, no additional cognitive benefit of HBO compared with NN was detected, and interference indices remained unchanged. In another study, Ramadan et al. (contribution 2) compared the hormonal responses in young women following a 10-week intervention of high-intensity interval training (HIIT) and traditional resistance training. Both exercise modalities were associated with significant increases in estrogen and reductions in testosterone, the follicle-stimulating hormone, and prolactin levels. Authors concluded that both exercise modalities may influence hormonal profiles, with potential implications for reproductive and metabolic health.

Other contributions in this Special Issue focused on the therapeutic potential of exercise interventions for the prevention and management of chronic health conditions. Moreales-Acuna et al. (contribution 3) demonstrated that a six-week boxing training program, performed three times per week, can be an effective and time-efficient strategy for improving vascular function and managing early stages of hypertension in young adults. Another study by Rad Bodan et al. (contribution 4) compared the effects of different eight-week intervention strategies on blood pressure, body mass index, and waist circumference in individuals with stage 1 hypertension, including healthy lifestyle recommendations (applied to all groups), antihypertensive medication (groups B, C, and D), a physical therapy program (group C), and hydrotherapy (group D). The results showed that interventions involving physical therapy and hydrotherapy resulted in greater improvements across these outcomes compared with lifestyle recommendations alone, even when patients needed to do programs without supervised support. Focusing on functional outcomes in older adults, Muanjai et al. (contribution 5) evaluated the effectiveness of an eight-week home-based stretching and strengthening training program for improving flexibility, muscle architecture, strength, and functional performance among individuals with leg tightness and/or suspected sarcopenia. The intervention improved flexibility, muscle strength, and functional performance, with strength-based exercises providing additional benefits, including muscle hypertrophy in knee extensors, suggesting that home-based exercise programs may represent a practical strategy to enhance physical function in older adults.

Additional contributions in this Special Issue explored the role of exercise interventions in clinical populations, with particular attention to mental health and well-being, as well as evidence-based exercise prescription. The study by Santos et al. (contribution 6) compared the effects of different supervised eight-week resistance training programs on mental health and well-being in individuals with spinal cord injury. Traditional resistance training showed the greatest improvements in anxiety, depression, and quality of life, whereas flywheel resistance training and high-velocity resistance training also produced beneficial, though more modest, effects. A scoping review by Peña et al. (contribution 7) aimed to characterize the load components of resistance training programs for kidney transplant recipients. The review highlighted the lack of standardized prescription criteria while providing evidence-based recommendations for training intensity, volume, and load progression that may serve as a reference for exercise professionals in designing resistance training programs for this population. Mena-Jiménez et al. (contribution 8) also conducted a scoping review on the return to physical activity in individuals with surgical stomas within the context of post-surgery rehabilitation. The authors found that current evidence is limited and heterogeneous, with most studies focusing on adult and oncology patients.

https://doi.org/10.3390/sports14050183

The review highlights the need for more rigorous research and clearer guidance regarding the type, frequency, and intensity of exercise necessary to support safe participation in physical activity, avoid stoma-related complications, and improve quality of life in this population.

Other studies also explored the role of physical activity and sport in promoting motor development and psychological well-being in children and adolescents. Bekmanova et al. (contribution 9) compared the effectiveness of 12-week mini-handball training and conventional motor skill training (three sessions a week) on coordination in children with developmental coordination disorder. Results showed that both interventions improved coordination compared with the control group, although the mini-handball program produced greater improvements, particularly in tasks requiring anticipatory control and visuomotor integration. These findings seem to support the inclusion of sport-based, open-skill interventions in therapeutic and community programs, as well as in school curricula. The study of Di Martino et al. (contribution 10) raises another important question, aiming to evaluate whether physical activity and sports may act as protective factors in mitigating the long-term consequences of the COVID-19 pandemic in children and adolescents. Findings showed that four years after the pandemic, high percentage of anxiety and depression disorders remain among youth population. Sport participation appears to mitigate these effects, as adolescents with sport training experience showed lower depression rates.

Other studies also contribute to a better understanding of knowledge, performance, and safety in physical activity and sport settings. The study of Kobayashi et al. (contribution 11) conducted a cross-sectional survey with 1000 adults aged 20–69 years old to examine knowledge related to strength training, including the understanding of targeted muscle groups and proper exercise form. The results suggested that individuals with strength-training experience demonstrated higher knowledge across both domains, whereas those with instructional experience scored higher in knowledge of exercise form and movement. Lastly, the study of Berasategui et al. (contribution 12) described the physical responses of female football players with cerebral palsy during the 2022 Women's World Cup and compared the responses according to the players' sport class. Players classified as FT1 demonstrated lower physical responses during matches than those in FT2 and FT3, whereas similar performance profiles were observed between the FT2 and FT3 groups.

3. Concluding Remarks

Collectively, the studies included in this Special Issue reinforce the importance of physical activity and exercise across diverse populations and contexts. The contributions provide valuable insights into physiological responses to exercise, its role in the prevention and management of chronic conditions, and its potential to enhance functional capacity, motor development, and psychological well-being. Some studies also address practical aspects related to exercise prescription and safe participation in sport and physical activity, particularly in clinical populations.

Importantly, the presented evidence spans a range of research approaches, including experimental studies, randomized controlled trials, observational studies, and scoping reviews, and involves diverse populations from children and adolescents to adults, older adults, and clinical groups. This methodological and population diversity provides a broader perspective on current research and practice in physical activity and exercise.

Considering the high global prevalence of physical inactivity, these findings highlight the continued importance of research that supports safe, effective, and context-specific approaches to promoting physical activity and exercise across populations.

https://doi.org/10.3390/sports14050183

Author Contributions: Writing—original draft preparation, R.F. and F.M.S.; writing—review and editing, R.F., H.P.N. and P.D.-M. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by National Funds by FCT—Foundation for Science and Technology, under the projects UID/04045/2025 (https://doi.org/10.54499/UID/04045/2025), UID/PRR/04045/2025 (https://doi.org/10.54499/UID/PRR/04045/2025) and UID/PRR2/04045/2025. (https://doi.org/10.54499/UID/PRR2/04045/2025).

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

Abbreviations

The following abbreviations are used in this manuscript:

HBO	Mild hyperbaric oxygen
NN	Normobaric normoxia
HIIT	High-intensity interval training

List of Contributions

1. Nakao, T.; Hirata, T.; Adachi, T.; Fukuda, J.; Fukada, T.; Iino-Ohori, K.; Igarashi, M.; Yoshikawa, K.; Iwasa, K.; Saito, A. Cognitive Processing Efficiency (Throughput) Improves with Aerobic Exercise and Is Independent of the Environmental Oxygenation Level: A Randomized Crossover Trial. *Sports* **2026**, *14*, 30. https://doi.org/10.3390/sports14010030.
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Article

Cognitive Processing Efficiency (Throughput) Improves with Aerobic Exercise and Is Independent of the Environmental Oxygenation Level: A Randomized Crossover Trial

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Abstract

Aerobic exercise with eicosapentaenoic acid (EPA) may enhance cognition via cerebrovascular pathways. We tested whether mild hyperbaric oxygen (HBO; 1.41 atmospheres absolute [ATA], approximately 30% O_2) adds to gains in cognitive processing capacity (throughput) versus normobaric normoxia (1.0 ATA, approximately 21% [20.9%] O_2). Healthy young adults (n = 16) performed cycling exercise at 60–70% VO_{2peak} for 60 min, twice weekly, for 4 weeks per environment with a 1-week washout; EPA (2170 mg·day^{-1}) was taken during each 4-week training phase (total 8 weeks) and was paused during the washout. An EPA-only control (n = 8) was included for supplementary analysis. The primary outcome was throughput (correct·min^{-1}; T1–T4); secondary outcomes were interference indices (I1: stroop interference, I2: reverse-stroop interference). Effects were estimated using linear mixed models [environment, time, environment × time; AR(1), REML] and Hedges' g_{av}; accuracy used generalized estimating equations. Throughput improved mainly with time (T1–T2 $p < 0.001$; T4 $p = 0.017$; T3 $p = 0.055$), with no environment or interaction effects. I1/I2 showed no significant change, and one task exhibited an accuracy ceiling. Under safe, feasible conditions (≤1.41 ATA), aerobic exercise improved processing capacity (throughput) independently of environmental oxygenation level. The absence of detectable additive effects should be interpreted cautiously under conservative settings.

Keywords: aerobic exercise; cognitive function; brain-vascular pathways; eicosapentaenoic acid; oxygen level

1. Introduction

Aerobic exercise enhances higher-order cognitive functions, such as attention and inhibitory control, by optimizing neurovascular units, primarily in the prefrontal cortex [1]. The hyperbaric oxygen (HBO) environment, which artificially modifies the available oxygen during exercise, increases the partial pressure of arterial blood oxygen and tissue oxygenation level, thereby influencing peripheral and cerebral circulation dynamics [2]. However, few

studies have examined how exercise under hyperbaric oxygen (HBO) conditions—which can alter systemic and cerebral circulation—affects cognitive processing, including Stroop task throughput and interference. Furthermore, although eicosapentaenoic acid (EPA), an n-3 polyunsaturated fatty acid with anti-inflammatory and neuroprotective properties, may enhance these outcomes, its potential benefit when combined with HBO exercise remains largely unexplored. A recent preprint from our group (not yet peer-reviewed) reported that during exercise in an HBO environment, red blood cell count and hematocrit decreased whereas hemoglobin concentration remained stable, supporting a preliminary hypothesis that reduced blood viscosity and preserved oxygen-carrying capacity can coexist and may promote more efficient micro-circulation [3]. Furthermore, EPA supports neurovascular coupling reactivity by alleviating vascular inflammation and improving rheological properties [4,5]. Given these findings, HBO with exercise with EPA is expected to enhance the "functional reserve" of networks involved in conflict resolution and response selection, thereby boosting both the speed and accuracy of interference suppression. However, performance on the Stroop task is susceptible to the "speed-accuracy tradeoff," and relying solely on reaction time or accuracy rates risks underestimating or overestimating the intervention effect [6]. Therefore, in the present trial we pre-specified throughput (correct responses per minute; correct·min^{-1}) as the primary cognitive outcome, because it combines speed and accuracy into a single index of processing efficiency and is expected to be less susceptible to changes in the speed–accuracy tradeoff. In addition, The interference indices (I1/I2) and accuracy were analyzed as secondary outcomes to provide complementary information about where changes may emerge within the processing pipeline (perception, conflict resolution, and response selection) [7,8].

Furthermore, this study envisions future applications in space medicine. Astronauts perform tasks in spacesuits (typically 0.3 atm, 100% oxygen), effectively executing cognitive tasks in an environment equivalent to approximately 30% of terrestrial oxygen levels (ppO_2 = PB × FiO_2; where ppO_2 is inspired oxygen partial pressure, PB is barometric pressure, and FiO_2 is the fraction of inspired oxygen) [9]. However, the mild HBO condition used in this study is not intended to directly simulate such operational environments; thus, any potential applications to space medicine should be considered hypothetical, not directly supported by the present data, and interpreted with caution. This study provides foundational data to verify the effects of oxygen availability on cognitive function.

This study aimed to simultaneously examine aerobic exercise in an HBO environment and EPA intake within a randomized crossover framework in humans, clarifying their effects on speed-accuracy integrated performance (throughput) and speed-based interference (I1/I2). The primary hypothesis predicted that throughput would improve over time, regardless of environmental condition, reflecting the combined effects of exercise training and task learning. An exploratory hypothesis proposed that increased oxygen availability under HBO conditions might confer additional benefits, potentially appearing as an environmental main effect or an environment × time interaction. For the interference indices (I1/I2), we further hypothesized a directional decrease, with lower values indicating reduced interference, while expecting only small effect sizes given the short intervention period.

The present study provides three additions to the existing evidence base on mild HBO, exercise, and EPA supplementation, summarized in three points. First, in healthy young adults, we used a randomized crossover design to evaluate, within a single protocol, the combined effects of mild HBO exposure, aerobic exercise training, and EPA supplementation, thereby complementing prior studies that have often examined HBO or EPA separately and/or in clinical or mixed populations. Second, we selected throughput—a speed–accuracy integrated metric—as the primary cognitive outcome and used interference indices (I1/I2) as secondary measures, providing a processing-efficiency perspective beyond studies that often relied mainly

https://doi.org/10.3390/sports14010030

on accuracy or reaction time alone. Third, we interpreted the observed cognitive changes within a physiological working model in which possible reductions in blood viscosity and preserved oxygen transport may influence cerebrovascular function, offering a hypothesis-generating framework that links exercise cognitive science with environmental physiology and nutritional science.

2. Materials and Methods

2.1. Study Design

This was a randomized crossover trial (Figures 1 and 2) with a mixed design, combining a 2 × 2 within-subject crossover of HBO and normobaric normoxia (NN) with a parallel control group that received only EPA. Participants were divided into three groups. Two groups performed supervised cycling training under either HBO or NN conditions while simultaneously taking EPA daily: the HBO + exercise + EPA and the NN + exercise + EPA (randomized cross over 2 group). Subsequently, the crossover groups switched environments and repeated an identical protocol. The third group consumed only EPA without exercise and served as the EPA control group under the NN conditions (non-randomized EPA-only group). Each trial lasted for 4 weeks, with a 1-week washout period based on prior research on plasma EPA half-life [10–12]. Health examinations and measurements were conducted before, during, and after the experiments. This study was conducted in accordance with the principles of the Declaration of Helsinki and was approved by the Ethics Committee. Written informed consent was obtained from all the participants. The primary analysis focused on the crossover group (environment × time), whereas the EPA control group was included in the secondary analysis. This study was conducted as an experimental study on exercise and environmental physiology and not for medical purposes.

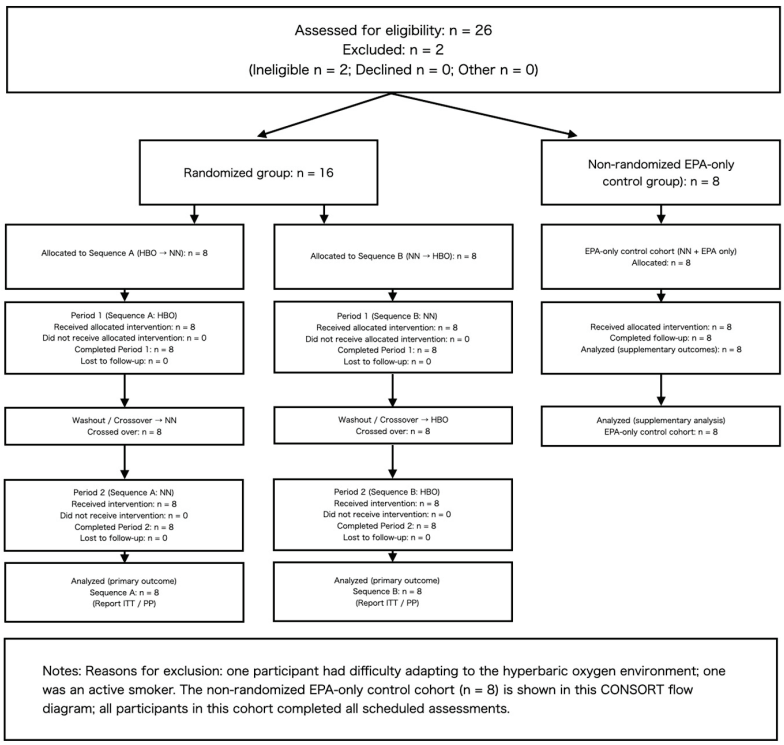


Figure 1. CONSORT flow diagram for the randomized two-period crossover trial with an additional non-randomized EPA-only control cohort. Twenty-six individuals were assessed for eligibility; two were excluded (one could not adapt to the hyperbaric oxygen environment; one was an active

https://doi.org/10.3390/sports14010030

smoker). Sixteen participants were randomized (Sequence A: HBO → NN, n = 8; Sequence B: NN → HBO, n = 8), completed both periods, and were included in the primary analysis. A non-randomized EPA-only control cohort (NN + EPA only, n = 8) also completed all scheduled assessments and was included in secondary supplementary analyses.

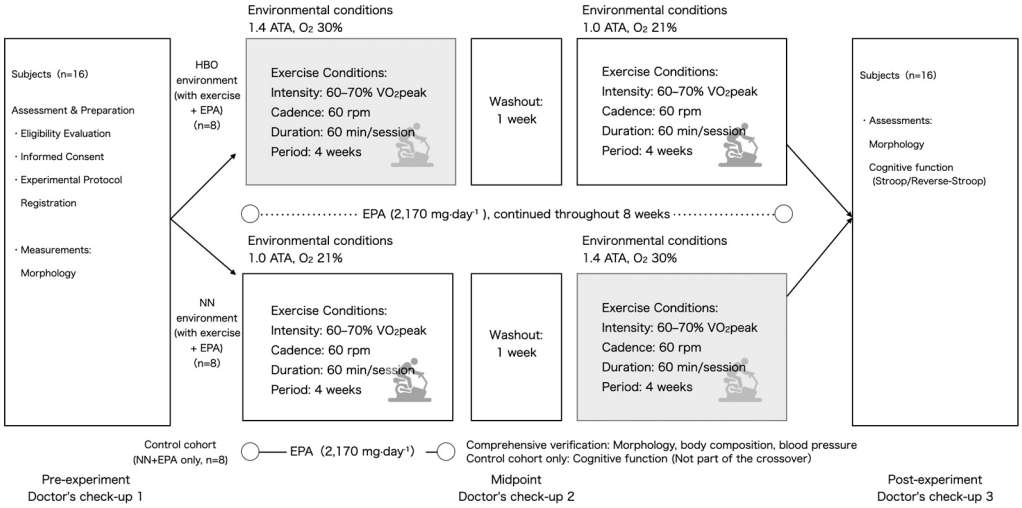


Figure 2. Randomized two-period crossover design. Participants (n = 16) completed two 4-week exercise phases under hyperbaric oxygen (HBO; 1.41 ATA, O_2 30%) or normobaric normoxia (NN; 1.0 ATA, O_2 20.9%) environments in a randomized order, separated by a 1-week washout. EPA supplementation (2170 mg·day^{-1}) was taken during both 4-week phases (total 8 weeks) and paused during the washout. Assessments were performed before and after each phase (morphology, body composition, blood pressure, and cognitive function [Stroop/Reverse-Stroop]). The midpoint corresponds to the end of Phase 1 (Period 1 post) and, simultaneously, the start of Phase 2 (Period 2 pre) in the primary crossover analysis. Optional: A separate control cohort (NN + EPA only; non-randomized EPA-only group, n = 8) followed the same assessment schedule without crossover; this cohort was not part of the randomized crossover and is summarized in Supplementary Tables S1–S3. Oxygen fraction values in the schematic are rounded to the nearest integer; for example, 20.9% is shown as 21%. ATA, atmosphere absolutes; EPA, eicosapentaenoic acid.

2.2. Participants

The participants were recruited between 25 April and 18 June 2024, through university bulletin boards and online announcements, including posts on social media. Twenty-four healthy adult males (mean ± standard deviation: age, 20.9 ± 1.4 years; height, 171.4 ± 5.6 cm; weight, 64.1 ± 11.6 kg; and body mass index (BMI), 21.8 ± 3.6 kg/m^2) were randomly assigned to the HBO + exercise + EPA, NN + exercise + EPA, or EPA control groups (n = 8 per group). The inclusion criteria were as follows: no history of cardiovascular or metabolic disease, no history of smoking, ability to perform moderate-intensity exercise and take EPA-containing supplements during the study period, and ability to adapt to hyperbaric environments. The exclusion criteria were as follows: age < 20 years, excessive exercise habits, and requiring specific foods and/or supplements. Participants were instructed to avoid significant changes in their diet or lifestyle during the study period. The sample size estimation assumed a conventional medium effect size (f = 0.25) for a 2-group × 2-time point comparison in the absence of pilot data, using conservative assumptions (correlation among repeated measures = 0.50; ε = 1). It should be noted that this was a conservative setting for the crossover design that included within-subject comparisons; therefore, the sample size estimation should be interpreted cautiously.

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2.3. Experimental Environment

2.3.1. Environment

In the HBO environment, absolute pressure of 1.41 ± 0.01 ATA, oxygen concentration of 29–30%, temperature of 21.7 ± 0.7 °C, and humidity of 73.5 ± 4.6% were maintained. These settings were selected primarily based on the chamber's certified operating limit for mild HBO operation (Type II; ≤1.41 ATA) and to remain within commonly used mild-HBO ranges reported in prior work [13]. The NN environment maintained an absolute pressure of 1.00 ± 0.01 ATA, an oxygen concentration of 20.9% (≈21%), a temperature of 22.1 ± 1.1 °C, and a humidity of 70.5 ± 6.5%. The HBO environment was constructed in an artificial environmental control chamber (Japan Pressure Bulk Industries Co., Ltd., Shizuoka, Japan) at a pressurization/depressurization rate of 0.07 ATA/min. A bicycle ergometer (STB-3400; Nihon Kohden Co., Ltd., Tokyo, Japan) was installed inside the chamber. The NN environment is established in a standard laboratory equipped with a similar facility. The hyperbaric chamber used complied with domestic operational safety standards (mild HBO Type II, ≤1.41 ATA) and was distinguished from medical treatment devices.

2.3.2. Eligibility Assessment, Pre-Experimental Measurements, and Medical Examination

Before enrolling for the experiment, the participants underwent a preliminary interview, supervised cycling training (peak oxygen uptake [VO_{2peak}] measurement), and an assessment of their ability to adapt to the HBO environment. Medical examinations were performed by a physician. All outcome measures were assessed at three time points: baseline (before the first 4-week intervention phase), immediately after the first 4-week phase (before the 1-week washout), and after completion of the second 4-week phase. In the primary crossover analysis, the midpoint assessment served as the Period 1 post value and the Period 2 pre value and was not treated as an independent endpoint.

2.3.3. Anthropometric Measurements

Height was measured using a standard height gauge (A&D Co., Ltd., Tokyo, Japan). Weight and body composition parameters (fat-free mass [FFM], fat mass [FM], and fat mass percentage [% FM]) were assessed using a dedicated bioelectrical impedance analyzer (InBody 770; InBody Japan Co., Ltd., Tokyo, Japan). Based on these measurements, the BMI was calculated using the following formulas: BMI = weight (kg)/height^2 (m^2). Systolic blood pressure and diastolic blood pressure were measured using an automatic upper arm blood pressure monitor (HBP-1300; Omron Co., Ltd., Kyoto, Japan) via an oscillometric method.

2.3.4. Exercise Load

The exercise intensity for the bicycle ergometer test was set at 60–70% of the VO_{2peak}. The pedaling speed was 60 rpm, and each session lasted 60 min. The test was conducted twice a week for 4 weeks. Before the intervention, VO_{2peak} was estimated using the breath-by-breath method with a respiratory metabolic monitoring system (AE-310S; Minato Medical Science Co., Ltd., Osaka, Japan). Exercise in the HBO environment was performed for 60 min after reaching the predetermined absolute pressure. The time required for pressurization and decompression was approximately 20 min. Participants in the HBO group exercised in the HBO environment during the first phase and in the ambient-pressure environment during the second phase, while those in the ambient-pressure group exercised in the reverse order. All exercise sessions were conducted in person under direct supervision by research staff, and adherence was monitored through individual training logs documenting attendance at each scheduled session. All participants completed 100% of their prescribed sessions. The effects of the sequence and timing were examined using sensitivity analyses in the statistical analysis.

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2.3.5. EPA Intake

During the study period, participants were instructed to take a high-concentration EPA supplement (Bizen Chemical Co., Ltd., Akaiwa, Japan) at 2170 mg daily in capsule form. The EPA intake overlapped with the exercise period in both environments and was suspended before study initiation and during the 1-week washout. Adherence was monitored by capsule counts from pre-packed supplies and by a daily online log in which participants recorded intake status, gastrointestinal symptoms, and stool characteristics. The EPA dosage was food-grade and within the recommended range for dietary reference intake in Japan [14].

2.3.6. Cognitive Function Assessment: Throughput, T1–T4, and I1–I2

The New Stroop Test II (Toyophysical Co., Ltd., Fukuoka, Japan) was used to administer four tasks: T1 Reverse Stroop Control (semantic selection with no interference), T2 Reverse Stroop Interference (semantic selection with color ink interference), T3 Stroop Control (color name selection with no interference), and T4 Stroop Interference (color name selection with semantic interference) [15,16]. Each block was a 60 s self-paced response task with a randomized stimulus presentation and counterbalanced block order. Primary outcomes were throughput (correct responses per minute; correct·min^{-1}), integrating speed and accuracy; secondary outcomes included interference indices (I1/I2); and reference outcomes include accuracy (correct response rate). Throughput (T1–T4) was calculated as the number of correct responses in each 60 s block (errors and omissions excluded) and expressed as correct responses per minute (correct·min^{-1}). Interference indices were defined as I1 = (T3 − T4)/T3 and I2 = (T1 − T2)/T1. Accuracy was defined as a correct/incorrect response. Interpretation was based on both the p-value (Holm-corrected) and effect size [Hedges' g_{av}·95% CI]. Positive values indicate improved throughput (increase), whereas decreases in I1/I2 indicate reduced interference. All cognitive measurements were conducted under NN immediately before and after each 4-week training phase. The testing environment was standardized to NN to isolate on the long-term effects of regular training rather than acute HBO exposure, and because administering the full cognitive protocol inside the HBO chamber was not feasible for practical and safety reasons.

2.3.7. Statistical Analysis

Analyses were performed using IBM SPSS Statistics ver.27 (IBM Corp., Armonk, NY, USA). The primary (throughput) and secondary outcomes (I1/I2) were analyzed using linear mixed models (LMM). Fixed effects included environment (HBO/NN), time (Post/Pre), and their interaction. Random effects included the participant ID intercept. The repeated-measures covariance structure was first-order autoregressive (AR(1)), and the estimation was based on the restricted maximum likelihood (REML). Assumptions of the LMMs (normality and homoscedasticity of residuals) were evaluated using Q–Q plots and residual-versus-fitted plots, and no meaningful deviations were observed. Fixed effect tests used Type-III Wald χ^2 (df = 1), and estimates were reported as coefficient ± standard error (SE) and 95% confidence interval (CI). The effect size for within-group change was determined using Hedges' g_{av} (95% CI). The reference outcome (accuracy) was analyzed using generalized estimating equations (GEE; binomial logit, exchangeable, and robust SE). Effect measures are reported as odds ratios (ORs) and 95% CI. Multiplicity was corrected using Holm's method. The significance level was set at $\alpha = 0.05$ (two-tailed), and no additional exploratory significance threshold (e.g., $p < 0.10$) was prespecified; p-values above 0.05 were interpreted descriptively. Because the sample size ($n = 16$) was constrained by practical and budgetary factors, a post hoc G*Power 3.1 calculation for a 2 (environment: HBO vs. NN) × 2 (time: pre vs. post) repeated-measures analysis of variance (within–

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between interaction), assuming a correlation of 0.50 among repeated measures ($\varepsilon = 1$), indicated adequate power ($1–\beta > 0.80$) only for large effects (approximately $f = 0.50$). Detecting a medium effect ($f = 0.25$) would require 34 participants in total. This study should therefore be considered exploratory, with limited power for small-to-moderate effects, and results were interpreted with greater emphasis on estimated coefficients, their 95% confidence intervals (CIs), and effect sizes rather than *p*-values alone.

3. Results

3.1. Summary

The environment × time interaction and the main effect of the environment were not significant. However, the main effect of time was significant at T1 ($p < 0.001$, 95% CI 2.63–7.49), T2 ($p < 0.001$, 95% CI 2.59–6.59), T4 ($p = 0.017$, 95% CI 0.40–4.16), whereas the time effect at T3 did not reach the predefined significance level ($p = 0.055$, 95% CI −0.03–3.53; Figure 3). Across all tasks (T1–T4), accuracy was already very high and showed minimal variation across environments and time points. Accuracy in Task 3, in particular, was 100% in all conditions (Supplementary Table S2).

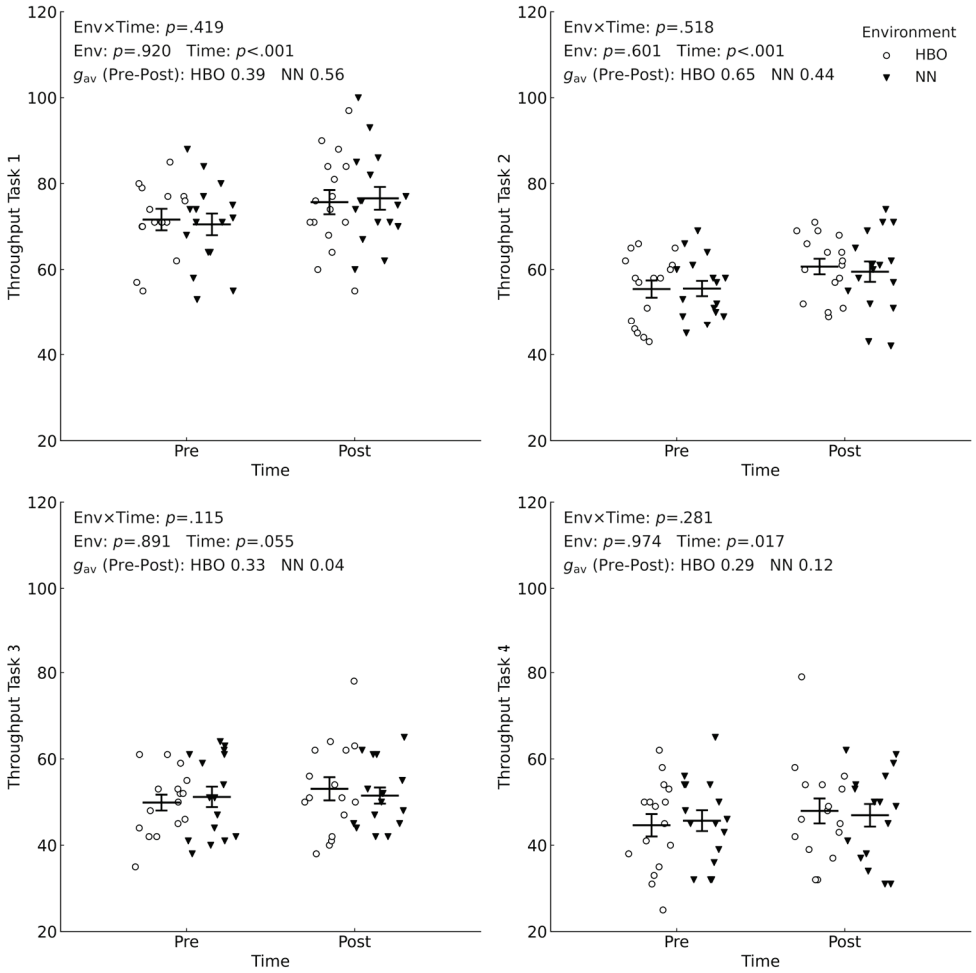


Figure 3. Throughput performance in Stroop tasks (T1–T4) by environment (HBO vs. NN) and time (pre vs. post). Short horizontal bars indicate group means and T-shaped error bars indicate the standard error. Symbols represent individual participant values with minor horizontal jitter for visibility. White circles, HBO; black triangles, NN. Throughput, correct·min^{-1}. HBO, hyperbaric oxygen; NN, normobaric normoxia.

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3.2. Physical Characteristics

Table 1 shows the descriptive statistics (mean ± standard deviation) for each group before and after the intervention. The interaction effect of the environmental conditions and time was not significant for any of the following variables: height, weight, BMI, body composition parameters, or blood pressure. No significant changes in the physical characteristics were observed in the EPA control group (all $p > 0.050$).

Table 1. Participant characteristics before and after the intervention in the HBO + exercise + EPA group, the NN + exercise + EPA group, and the NN + EPA group.

Measurement		HBO + Ex + EPA		NN + Ex + EPA		NN + EPA		*p* Value Environment × Time Interaction
		Pre	Post	Pre	Post	Pre	Post	
Height	cm	170.4 ± 5.9	170.3 ± 5.9	170.7 ± 6.0	170.4 ± 5.9	172.9 ± 5.0	172.6 ± 5.2	0.113
Weight	kg	65.1 ± 11.4	65.8 ± 11.8	64.5 ± 12.0	64.9 ± 11.0	63.3 ± 12.3	63.5 ± 12.3	0.588
BMI	kg/m^2	22.3 ± 2.9	22.5 ± 3.1	22.0 ± 3.3	22.3 ± 2.9	21.2 ± 4.5	21.4 ± 4.6	0.975
FFM	kg	52.2 ± 6.9	52.7 ± 7.2	52.3 ± 7.3	52.0 ± 6.5	55.0 ± 7.8	54.6 ± 7.1	0.108
FM	kg	12.9 ± 5.3	13.1 ± 5.5	12.2 ± 5.6	13.0 ± 5.5	8.3 ± 5.6	8.9 ± 5.8	0.260
%Fat	%	19.2 ± 4.8	19.3 ± 4.9	18.3 ± 4.8	19.4 ± 5.1	12.4 ± 5.1	13.2 ± 5.2	0.137
SBP	mmHg	115.7 ± 9.6	117.6 ± 7.6	116.4 ± 7.3	114.2 ± 9.5	115.0 ± 10.9	114.8 ± 11.2	0.107
DBP	mmHg	61.0 ± 5.9	61.4 ± 6.8	60.1 ± 7.0	61.3 ± 6.9	63.1 ± 9.7	61.9 ± 7.0	0.806

3.3. Cognitive Processing Efficiency (Throughput)

Figure 3 shows the pre- and post-intervention throughputs of the HBO + exercise + EPA group and the NN + exercise + EPA group. No interactions were observed across any of the four tasks (T1: $p = 0.419$, T2: $p = 0.518$, T3: $p = 0.115$, T4: $p = 0.281$), and the main effect of the environment was also nonsignificant (T1, $p = 0.920$, T2, $p = 0.601$, T3, $p = 0.891$, T4, $p = 0.974$). In contrast, the main effect of time was significant at T1 and T2 (both $p < 0.001$), significant at T4 ($p = 0.017$), and did not reach significance at T3 ($p = 0.055$), indicating that the throughput improved after the intervention regardless of the environment. The magnitude of the pre- and post-intervention difference (Hedges' g_{av}) varied by task: T1-HBO, 0.39; NN, 0.56; T2-HBO, 0.65; NN, 0.44; T3-HBO, 0.33; NN, 0.04; T4-HBO, 0.29; and NN, 0.12. According to conventional benchmarks (0.2, 0.5, and 0.8 representing small, medium, and large effects, respectively), the improvements in throughput at T1 and T2 can be interpreted as small to medium in magnitude—particularly in NN at T1 ($g_{av} = 0.56$) and HBO at T2 ($g_{av} = 0.65$)—whereas the effects at T3 and T4 were small or trivial regardless of environment. Figure 3 shows individual data points and estimated marginal means ± SE, with units expressed as correct·min^{-1}.

3.3.1. T1–T4 and I1–I2: LMM Test Table

In the LMM for T1–T4 based on unstandardized throughput values (correct·min^{-1}), no environment×time interaction was detected (Table 2) (T1: $\chi^2 = 0.654$, $p = 0.419$; T2: $\chi^2 = 0.417$, $p = 0.518$; T3: $\chi^2 = 2.491$, $p = 0.115$; T4: $\chi^2 = 1.161$, $p = 0.281$). No main effect of the environment was observed either (T1: $\chi^2 = 0.010$, $p = 0.920$; T2: $\chi^2 = 0.274$, $p = 0.601$; T3: $\chi^2 = 0.019$, $p = 0.891$; T4: $\chi^2 = 0.001$, $p = 0.974$). On the other hand, the main effect of Time (post vs. pre) on throughput was significant at T1 (coefficient = 5.062 correct·min^{-1}, 95% CI 2.63–7.49, $\chi^2 = 16.757$, $p < 0.001$), T2 (coefficient = 4.594 correct·min^{-1}, 95% CI 2.59–6.59, $\chi^2 = 20.457$, $p < 0.001$), and T4 (coefficient = 2.281 correct·min^{-1}, 95% CI 0.40–4.16, $\chi^2 = 5.682$, $p = 0.017$), whereas the time effect at T3 did not reach the predefined significance level (coefficient = 1.750 correct·min^{-1}, 95% CI −0.03–3.53, $\chi^2 = 3.692$, $p = 0.055$).

https://doi.org/10.3390/sports14010030

Table 2. The Type-III Wald χ^2 (df = 1) test results for fixed effects in the LMM.

Task	Effect	Coef	SE	95% CI (Low)	95% CI (High)	Wald $\chi^2(1)$	p
T1	Env × Time	2.000	2.47	−2.84	6.84	0.654	0.419
	Environment	−0.125	1.24	−2.56	2.31	0.010	0.920
	Time	5.062	1.24	2.63	7.49	16.757	$p < 0.001$
T2	Env × Time	−1.312	2.03	−5.29	2.67	0.417	0.518
	Environment	−0.531	1.02	−2.53	1.47	0.274	0.601
	Time	4.594	1.02	2.59	6.59	20.457	$p < 0.001$
T3	Env × Time	−2.875	1.82	−6.44	0.69	2.491	0.115
	Environment	−0.125	0.91	−1.91	1.66	0.019	0.891
	Time	1.750	0.91	−0.03	3.53	3.692	0.055
T4	Env × Time	−2.062	1.91	−5.81	1.68	1.161	0.281
	Environment	0.031	0.96	−1.85	1.91	0.001	0.974
	Time	2.281	0.96	0.40	4.16	5.682	$p = 0.017$
I1	Env × Time	1.750	2.47	−3.08	6.58	0.503	0.478
	Environment	1.500	1.23	−0.92	3.92	1.479	0.224
	Time	0.188	1.23	−2.23	2.60	0.023	0.879
I2	Env × Time	−1.500	2.27	−5.95	2.95	0.436	0.509
	Environment	1.000	1.14	−1.23	3.23	0.776	0.378
	Time	0.063	1.14	−2.16	2.29	0.003	0.956

3.3.2. T1–T4 and I1–I2: Effect Sizes Within the Same Environment

For within-environment changes (Hedges' g_{av}), throughput improvements were largest at T2 (Table 3), with a clear improvement also at T1, whereas T3 and T4 showed at most small and imprecise effects. Using conventional benchmarks (0.2, 0.5, and 0.8 representing small, medium, and large effects, respectively), the effect sizes for HBO were small at T1 (g_{av} = 0.39, 95% CI 0.05–0.74), medium at T2 (0.65, 0.42–0.88), and small at T3 (0.33, −0.01–0.67) and T4 (0.29, −0.01–0.58). For NN, the effects were medium at T1 (0.56, 0.34–0.78), small to medium at T2 (0.44, 0.12–0.77), and trivial to small at T3 (0.04, −0.22–0.28) and T4 (0.12, −0.10–0.33). Overall, T1 and T2 showed small-to-medium improvements in throughput—particularly the moderate-to-large effects at T2 in HBO and at T1 in NN—whereas T3 and T4 showed at most small effects. For T3 and T4 in both environments, however, the 95% CIs frequently included zero, indicating substantial uncertainty and suggesting that these small effects should be interpreted with caution.

Table 3. The effect sizes (Hedges' g_{av}) before and after exposure to the same environment.

Env.	Task	g_{av} (Post-Pre)	95% CI (Low)	95% CI (High)
HBO	T1	0.39	0.05	0.74
	T2	0.65	0.42	0.88
	T3	0.33	−0.01	0.67
	T4	0.29	−0.01	0.58
	I1	−0.09	−0.57	0.39
	I2	0.09	−0.29	0.47
NN	T1	0.56	0.34	0.78
	T2	0.44	0.12	0.77
	T3	0.04	−0.22	0.28
	T4	0.12	−0.10	0.33
	I1	0.14	−0.50	0.78
	I2	−0.08	−0.52	0.37

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The effect sizes for the interference indices (I1/I2) were close to zero with wide CIs, indicating no meaningful changes in interference control in either environment (HBO: I1 = −0.09, −0.57–0.39, I2 = 0.09, −0.29–0.47; NN: I1 = 0.14, −0.50–0.78, I2 = −0.08, −0.52–0.37).

4. Discussion

This study used a randomized crossover design to examine the effects of supervised cycling training under an HBO/NN environment with concurrent EPA supplementation on processing efficiency (throughput) and interference indices (I1/I2) in Stroop-type cognitive tasks. First, although throughput consistently improved with time, the main effect of the environment and the environment × time interaction were not significant, and no short-term additive effect of EPA was observed. Furthermore, I1/I2 showed no significant changes, and the accuracy in one task was 100% across all conditions (Supplementary Table S2), suggesting a potential ceiling effect given the already very high accuracy and minimal variation across environments and time points. In practical terms, a higher throughput means that participants produced more correct responses in the same amount of time without losing accuracy, indicating an improvement in the overall processing efficiency in this Stroop-type task. Therefore, the observed enhancement in processing efficiency can be interpreted as primarily resulting from the progressive integration and optimization of speed and accuracy (semi-automation of response selection and efficient allocation of attentional resources) through regular aerobic exercise and task learning (repetition) [17–19], although potential influences such as placebo and expectation effects cannot be completely ruled out. At the same time, part of the time-related increase in throughput is likely attributable to task learning due to repeated exposure to the same Stroop task, as well as to inter-individual variability in responsiveness. This supports the notion that exercise produces generalizable facilitation across the processing pipeline and improves the efficiency of the entire Stroop task processing pipeline (perception to conflict resolution to response selection). Specifically, both behavioral measures (RT reduction and accuracy maintenance) and event-related potentials indicate that after aerobic exercise, resource allocation increases in the perception/stimulus evaluation stage (P2/P3), responsiveness to control demands in the conflict/inhibition stage (N2) improves, and consequently, response selection stabilizes and accelerates [20–22].

However, these findings do not imply that HBO is ineffective. Potential reasons for failing to detect additional benefits of HBO include that participants were healthy young adults with high baseline abilities and limited room for improvement, as reflected in the generally high accuracy and throughput levels observed in this study [23–25]. Second, the possibility that the mild HBO settings ($\leq$1.41 ATA), exercise intensity and frequency, and EPA dosage and duration did not reach physiological effect thresholds should be viewed as a hypothesis generated from this protocol, requiring direct physiological verification. Third, given the specific structure of the Stroop-type task used here—which may have been dominated by visual search and response selection—differences in oxygen availability seem unlikely to have meaningfully influenced the interference indices. The primary implication of this study is that improvements in processing efficiency can be achieved through exercise training and task repetition, independent of the environment. Therefore, any additive effects of HBO and/or EPA may have been undetectable within the doses, durations, test conditions, sample size, and evaluation metrics used in this study. Furthermore, this trial has methodological significance owing to its establishment and validation of protocol and measurement system (HBO settings, pressurization rate, exercise modality, and throughput as primary outcomes) that can be safely implemented in humans.

Furthermore, the lack of a significant change in I1/I2 suggests that interference control did not improve meaningfully in either environment. Several methodological factors may

https://doi.org/10.3390/sports14010030

explain this null finding. First, task learning may initially enhance processing speed and only later affect interference suppression. Second, the evaluation window (block length or measurement timing) may have been insufficient for detecting subtle changes, and the sensitivity of I1/I2 may have been limited under the present task conditions. Third, variance in the metric may have been constrained by ceiling or floor effects [26–28]. Fourth, interference indices may be relatively stable and may require a longer intervention duration or greater task difficulty to detect changes. This interpretation should be considered a methodologically grounded hypothesis that should be examined explicitly in future studies. Future work requires optimization of the interference intensity (incongruity ratio, stimulus probability, and conflict parameters) and task difficulty, along with refinement of the measurement design (block length and retest timing). In summary, the findings of this study can be coherently explained using a biphasic model. While motor adaptation (enhancement of efficiency in neurovascular units centered on the prefrontal cortex) and task learning (optimization of stimulus-response mapping) drive throughput increases, HBO/EPA likely has minimal effects or remains within the range of measurement sensitivity under the current conditions and participants. Based on prior literature, the proposed mechanisms may include three partly overlapping pathways. First, cerebral blood flow and neurovascular coupling may become more responsive to task demands [17–19]. Second, lactate signaling and mobilization of alternative fuels, such as medium-chain triglycerides, may stabilize substrate supply during short-duration, high-demand tasks [29–31]. Third, autonomic nervous system regulation, indexed by heart rate variability (HRV), may reduce reaction time variability and support more consistent performance [32–34]. However, these mechanisms are inferred from prior work rather than directly demonstrated here because physiological indicators were not measured concurrently. Therefore, they remain hypothetical and require direct verification through simultaneous physiological monitoring in subsequent research. Thus, our mechanistic interpretation should be regarded as hypothesis-generating. This study has several methodological limitations. First, the relatively small sample size reduced the statistical power of the data to detect small environmental and interaction effects. Second, complete blinding to the environmental conditions was not feasible because the participants could perceive changes in barometric pressure via the inner ear. Third, despite the randomized crossover design and washout period, order effects between the HBO and NN conditions could not be completely ruled out. Therefore, the present findings should be interpreted as preliminary and hypothesis-generating.

Immediate priorities for future research should include direct assessment of neurovascular–metabolic coupling through simultaneous measurements, such as functional near-infrared spectroscopy, electroencephalography, and HRV, as well as broadening the study population to include older adults, at-risk groups, and women. Additional work should optimize dose, duration, and frequency across all components of the intervention, including HBO parameters (partial pressure of oxygen, exposure time, and session frequency); exercise frequency, intensity, time, and type; EPA dose, and intervention duration. Further studies should also increase task difficulty to avoid ceiling effects (manipulating the mismatch ratio, stimulus presentation probability, and competition intensity) and refine the assessment timing to distinguish acute responses, delayed effects, and longitudinal changes. This research program of research should be systematically advanced to rigorously test the boundary conditions for additive effects—specifically, which doses, durations, and loads elicit them—and to evaluate the validity of the proposed mechanisms [1,35,36], thereby strengthening the external validity of the protocol established in this study.

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5. Conclusions

This randomized crossover study examined the combined effects of supervised cycling training under HBO and NN environments with concurrent EPA supplementation on processing efficiency (throughput) and interference indices (I1/I2) in Stroop-type cognitive tasks in healthy young men. Throughput improved over time irrespective of the environmental condition, whereas no additional short-term cognitive benefit of mild HBO and/or EPA was detected under the present protocol and I1/I2 remained unchanged. These findings indicate that under the present conditions with concurrent EPA supplementation, regular aerobic exercise under NN can induce modest improvements in time-pressured information processing, whereas any additive cognitive effect of mild HBO was, at most, too small to be detected in this cohort and setting.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/sports14010030/s1, Table S1: Model–based estimated marginal means (EMM) with 95% CIs by Environment (HBO/NN), Time (Pre/Post), and Task (T1–T4, I1–I2); Table S2: Accuracy (A1–A4): GEE odds ratios (Post vs Pre) and Type–III Wald tests; Table S3: Control cohort (NN+EPA): pre–post descriptive statistics, Hedges' gav (95% CI) for continuous outcomes (T1–T4, I1–I2), and GEE odds ratios for accuracy (A1–A4).

Author Contributions: T.N.: writing—review and editing, writing—original draft, methodology, investigation, visualization, data curation, funding acquisition, conceptualization. T.H.: writing—review and editing. T.A.: methodology, investigation, resources. J.F.: methodology, investigation, resources. T.F.: methodology, investigation, resources. K.I.-O.: writing—review and editing. M.I.: writing—review and editing, methodology, conceptualization. K.Y.: review and editing, methodology, data curation, funding acquisition, conceptualization, supervision. K.I.: writing—review and editing, funding acquisition. A.S.: writing—review and editing, writing—original draft, supervision, funding acquisition, conceptualization. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by MEXT KAKENHI (Grant Number 23K01975, 21K06807, 23K05122, 24K09866, and 25K18721).

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Ethics Committee of Kyushu Sangyo University (protocol code 2023-0006 and 18 December 2023 of approval)." for studies involving humans, and registered in the University Hospital Medical Information Network (ID: UMIN000057211).

Informed Consent Statement: Written informed consent has been obtained from the participants to publish this paper.

Data Availability Statement: The data sets used and analyzed during the current study are available from the corresponding author on reasonable request.

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

Abbreviations

ATA	atmosphere absolute
BMI	body mass index
DBP	diastolic blood pressure
EPA	eicosapentaenoic acid
FFM	fat-free mass
FM	fat mass
HBO	hyperbaric oxygen
NN	normobaric normoxia
O_2	oxygen

https://doi.org/10.3390/sports14010030

VO_{2peak}	peak oxygen uptake
%FM	percent fat mass
I1	stroop interference
I2	reverse-stroop interference
SBP	systolic blood pressure

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https://doi.org/10.3390/sports14010030

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Article

The Comparative Effects of High-Intensity Interval Training and Traditional Resistance Training on Hormonal Responses in Young Women: A 10-Week Intervention Study

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Abstract: Background: Hormonal levels in women are influenced by exercise intensity and modality. Methods: This 10-week study compared high-intensity interval training (HIIT) and traditional resistance training (TRT) in 72 young women. Hormonal levels (estrogen, testosterone, FSH, prolactin, and LH) were measured pre- and post-intervention. Results: Both groups showed significant increases in estrogen (HIIT: 150%; TRT: 72.3%) and decreases in testosterone (HIIT: 58%; TRT: 49%), FSH (HIIT: 6%; TRT: 7.7%), and PL (HIIT: 5%; TRT: 2.1%). There are no significant changes in LH. Conclusions: HIIT and TRT effectively modulate hormonal profiles, potentially benefiting reproductive and metabolic health.

Keywords: high-intensity interval training; traditional resistance training; physical fitness; hormonal responses

1. Introduction

Exercise training is widely recognized for its significant benefits to young women, including notable reductions in body fat and improvements in cardiovascular health [1–3]. Regular exercise has crucial effects on the hormonal profile, influencing key hormones such as testosterone, estrogen, prolactin, and follicle-stimulating hormone (FSH). These hormonal changes play critical roles in various physiological functions, including reproductive health, metabolism, and overall well-being. Testosterone, primarily known for its role in muscle growth and maintenance, is significantly influenced by exercise, particularly through traditional resistance training (TRT). Studies have consistently shown that TRT exercises, like weightlifting, increase testosterone levels in both men and women, promoting muscle hypertrophy and strength [4].

Estrogen is another hormone significantly influenced by exercise, with its effects varying depending on factors such as exercise intensity, duration, and individual physiological characteristics. The relationship between exercise and estrogen regulation is complex and may differ across populations and activity types. Endurance exercise, like long-distance running or swimming, is associated with reductions in estrogen levels in women, possibly due to changes in body fat composition and hormonal regulation [5,6]. Prolactin, a hormone crucial for lactation and reproductive function, also responds to exercise. Moderate- to high-intensity exercise can transiently increase prolactin levels, particularly in women, reflecting

the body's response to physical stress and metabolic demands [7]. Follicle-stimulating hormone (FSH), involved in reproductive health and the regulation of the menstrual cycle, may exhibit altered patterns with exercise, especially in women engaged in intense training or endurance activities. Changes in FSH levels can influence menstrual regularity and fertility, highlighting exercise as a factor in reproductive health management. Exercise plays a critical role in regulating hormonal dynamics, which are essential for maintaining overall physiological homeostasis. A comprehensive understanding of these effects is crucial for optimizing exercise interventions across different populations. This knowledge can inform the development of evidence-based exercise protocols for athletes, individuals seeking to enhance reproductive health, and those managing endocrine disorders [8].

High-intensity interval training (HIIT) exerts a profound influence on hormonal regulation, affecting key endocrine markers such as testosterone, estrogen, follicle-stimulating hormone (FSH), and prolactin. This training modality, characterized by repeated cycles of high-intensity exercise interspersed with recovery periods, has been shown to significantly elevate testosterone levels in both men and women. These hormonal adaptations contribute to enhanced muscle hypertrophy, improved metabolic efficiency, and optimized energy utilization, ultimately supporting physiological adaptations to exercise. [9,10]. Conversely, immediately post-exercise, it may transiently suppress estrogen in women, potentially influencing reproductive health and bone metabolism [11]. FSH, crucial for regulating ovarian function, may exhibit altered patterns in response to HIIT, affecting menstrual regularity and fertility [12]. Prolactin, a hormone primarily involved in lactation and reproductive function, exhibits a transient increase during and after high-intensity interval training (HIIT). This acute elevation is indicative of the body's neuroendocrine response to exercise-induced stress and the heightened metabolic demands associated with high-intensity exertion. The modulation of prolactin levels in response to HIIT underscores the complex interplay between exercise intensity, hypothalamic–pituitary axis activation, and endocrine regulation, with potential implications for performance optimization, recovery processes, and overall hormonal homeostasis [13].

Although exercise training has many physiological benefits, a potential adverse effect is primary or secondary amenorrhea, which may be precipitated by factors such as inadequate nutrition or low body mass. Both primary and secondary amenorrhea are characterized by the suppression of luteinizing and follicle-stimulating hormones. Furthermore, these conditions may involve the hypothalamic–pituitary–gonadal and hypothalamic–pituitary–adrenal axes [5].

It is worth highlighting that hypoestrogenism can adversely influence bone growth in athletes. Symptoms such as osteopenia, amenorrhea, and eating disorders are indicative of fatigue in female athletes. Girls who experience delayed menarche are more likely to have osteopenia, a higher prevalence of scoliosis, and increased stress characteristics compared to girls with typical menarche [14,15]. To maintain hormonal blood levels, it is necessary to achieve a balance between metabolism, production, and clearance rates. Various factors can disrupt this equilibrium, including vigorous physical activities, heat generation, competition-related stress, dietary restrictions, a decrease in body fat mass, and hypoxia [16]. Furthermore, consistent engagement in high-intensity exercise can result in menstrual irregularities, specifically oligomenorrhea, and can cause a disruption in the production of gonadotropins, leading to luteal phase deficiency and anovulation [17].

Prior research has shown that high-intensity and prolonged training can negatively impact female reproductive hormones. Evidence indicates that intense exercise can lead to disruptions in the circulation of female reproductive hormones and the hypothalamus–ovarian axis. These disruptions can be attributed to increased concentrations of stress hormones,

elevated leptin levels, and fatigue associated with low energy availability. This disruption could result in irregular menstrual cycles related to anovulation deficiency and luteal phase.

Recently, there has been attention on the patterns of exercise, particularly examining HIIT, which involves alternating vigorous exercise with lower-intensity exercise. Compared to more traditional continuous exercise, many studies have shown that HIIT holds promise for improving cardiovascular health-related factors such as insulin resistance, glucose uptake, vascular function, body adiposity, and blood pressure [18]. Additionally, there is evidence that combining aerobic and TRT exercise may be superior in improving the control of metabolic syndrome [19]. Despite extensive research on exercise-induced hormonal changes, few studies directly compare HIIT and TRT, particularly in healthy young women. Understanding these differences can help to optimize exercise interventions for hormonal health. These studies demonstrate the need for further examination of both the pattern of exercise and the combination of exercise modalities on the hormonal profile of young women, which is why we conducted the current study. This study aims to compare the effects of HIIT and TRT on levels of female hormones, including estrogen, testosterone, LH, FSH, and prolactin.

2. Materials and Methods

2.1. Participants

This study was designed as an intervention comparative study. Seventy-two healthy, physically active female college students were recruited for this study and randomly assigned to one of two experimental groups: high-intensity power training (HIPT) (n = 36) or traditional resistance training (TRT) (n = 36). The study followed a randomized controlled trial (RCT) design to minimize selection bias and enhance the validity of the findings. Participants were screened based on predefined exclusion criteria, which included pregnancy, smoking, a diagnosis of Type II diabetes, acute or chronic cardiovascular disorders, abnormal menstrual function (e.g., amenorrhea or irregular menstruation), contraindications to physical activity, and the use of hormonal supplementation [20]. All participants provided both oral and written informed consent after receiving a comprehensive explanation of the study's objectives, methodology, potential risks, and safety precautions. The study protocol was reviewed and approved by the Institutional Review Board (IRB) of the Faculty of Physical Education, Mansoura University, with the assigned ethics code 1175. The study was conducted in full compliance with the ethical principles outlined in the Declaration of Helsinki [21].

2.2. Study Design

Following the provision of informed consent, participants received detailed instructions on the movements included in the training protocol, as well as the procedures for performance assessments to ensure their safety and the proper execution of the exercises. Prior to the intervention, each participant underwent a comprehensive strength assessment to determine their maximal muscular strength for each movement prescribed in the training protocol, conducted on a designated testing day.

The intervention consisted of a 10-week structured training program, with sessions scheduled three times per week, resulting in a total of 30 training sessions. A minimum recovery period of 24 h was mandated between consecutive sessions to facilitate adequate physiological recovery. Participants underwent performance assessments both before and after the 10-week intervention to evaluate training-induced adaptations.

To monitor physical activity levels and training adherence, participants maintained a daily exercise log, documenting the duration, intensity, and type of exercise performed, along with their ratings of perceived exertion (RPE), subjective feedback regarding their physiological responses to the training, and any relevant observations regarding their general health [22].

2.3. HIPT Protocol

Participants were randomly assigned to one of two interventions: a standardized HIIT aerobic exercise training regimen combined with TRT, or a stretching exercise program. The program was designed to progressively reach the target volumes of 150–300 min of weekly exercise recommended for weight management [20]. Participants were instructed to engage in the prescribed exercise sessions on more than 5 days per week. Trained physical educators scheduled a weekly motivational call with the participants to assess intervention adherence, address barriers to exercise, and provide motivational counseling. Initially, all participants completed a 20 min HIIT exercise protocol consisting of alternating 2 min of brisk walking followed by 2 min of easy walking. Each week, the total exercise time increased by 5 min (to reach a total of 50 min of daily exercise), as tolerated, and the intervals of brisk walking increased in duration by 1 min until the participant could complete 5 min of brisk walking (followed by 2 min of easy walking). Participants had the option to complete the HIIT exercise in one or two sessions daily to reach the prescribed volume and pattern of exercise. The intensity of HIIT was set at 75–90% of maximum heart rate during the program. Throughout all exercise training sessions, participants were instructed to wear Polar watches to monitor their heart rates.

2.4. TRT Protocol

Participants assigned to the HIIT plus TRT intervention also completed a series of TRT exercises targeting the major muscle groups for 2 days a week for approximately 30 min. The exercises involved using elastic bands, light weights, and adapted bodyweight exercises. The program followed recommendations for TRT in healthy female individuals, and the intensity (resistance) of the exercises increased weekly, as tolerated [20]. The intensity of the weights used was approximately 60–80% of the one-rep max for the targeted number of repetitions.

2.5. Blood Samples

All blood samples were drawn by trained laboratory technicians under standardized laboratory conditions. The samples were then frozen, and assays using standardized methodologies were performed in one batch at the end of the study. Participants were asked to fast for a minimum of four hours before the blood samples were taken. The blood samples were drawn on the third day of the menstrual cycle. After collection, the samples were left to clot at room temperature for an hour and then centrifuged at 8000 rpm for 15 min at 4 °C. The obtained serum samples were stored at −20 °C until assay. Technicians separated clear, non-hemolyzed sera for use in assays of estrogen, testosterone, follicle-stimulating hormone (FSH), and luteinizing hormone (LH).

We measured hormonal concentrations using a solid-phase competitive chemiluminescent enzyme immunoassay, performed with the IMMULITE analyzer (Diagnostic Products Corporation, Los Angeles, CA. USA). This method was chosen for its established reliability, characterized by high sensitivity, specificity, and reproducibility in detecting circulating hormone levels. Venous blood samples were collected at two distinct time points: the baseline measurement, obtained prior to the initiation of the training protocol, and the post-intervention measurement, taken immediately following the final exercise session. This sampling strategy was designed to precisely evaluate the hormonal adaptations induced by the training intervention.

2.6. Data Analysis

Data were analyzed using the Statistical Package for the Social Sciences, version 27 (IBM Corp. Released 2020. IBM SPSS Statistics for Windows, Version 27.0. Armonk, NY,

USA: IBM Corp). Quantitative variables were tested for normality using the Shapiro test and were found to have a non-parametric distribution. These variables were presented as median (minimum–maximum). The Mann–Whitney test was used for comparisons between the two groups, and the Wilcoxon Signed Ranks Test was used for paired (pre–post) comparisons within each group. To study the effect of the interaction between groups and the phase of the study (pre–post), we applied the Non-Parametric Equivalent: Aligned Rank Transform (ART), which is a non-parametric method that can handle interactions in factorial designs. It allows for the analysis of interaction effects and main effects in non-parametric data that violate ANOVA assumptions using the R program. A p-value of $\leq$0.05 was considered statistically significant.

3. Results

The outcomes of the current experimental procedure are displayed, and the two groups are matched, with no significant differences between them regarding age, height, body mass, and BMI (Table 1).

Table 1. Age and anthropometry of two groups.

	HIIT Median (Min–Max)	**TRT Median (Min–Max)**	**Mann–Whitney Test (Independent Groups)**
Age (years)	18 (17–19)	18 (17–19)	$p \leq 0.82$
Height (cm)	167 (140–189)	166 (140–170)	$p \leq 0.22$
Body mass (kg)	65 (40–86)	65 (40–70)	$p \leq 0.45$
BMI (kg/m^2)	23.3 (20.4–24.3)	23.3 (20.4–24.2)	$p \leq 0.76$

HIIT—High-Intensity Interval Training; TRT—Traditional Resistance Training; BMI—Body mass index.

Table 2 shows that the two groups are matched in all hormone levels before training. Post-training, the levels of estrogen are significantly higher (45 $\pm$ 33 vs. 112.5 $\pm$ 41, and 65 $\pm$ 33 vs. 112 $\pm$ 42) with a p-value < 0.001 from pre- to post-training in the HIIT and TRT groups, respectively. Meanwhile, we found that testosterone levels are significantly lower (0.65 $\pm$ 0.18 vs. 0.27 $\pm$ 0.12, and 0.51 $\pm$ 0.44 vs. 0.26 $\pm$ 0.13) from pre- to post-training in the HIIT and TRT groups, respectively. The two groups showed significant increases in estrogen (HIIT: 150%; TRT: 72.3%) and decreases in testosterone (HIIT: 58%; TRT: 49%), FSH (HIIT: 6%; TRT: 7.7%), and PL (HIIT: 5%; TRT: 2.1%). There is no significant change in LH between the two groups.

Table 2. Hormones of 2 groups pre- and post-intervention.

	HIIT Median (Min–Max)	**TRT Median (Min–Max)**	**Mann–Whitney (Independent Groups)**	**Aligned Rank Transform (ART)**
Estrogen: Pre	45 (33–66)	65 (53–86)	$p \leq 0.84$	Group Effect: F (1, 70) = 13.67, $p < 0.001$
Post	112.5 (90–131)	112 (91–133)	$p \leq 0.001$	Time Effect: F (1, 70) = 2722.47, $p < 0.001$
% change	+150.0	+72.3		Group $\times$ Time Interaction: F (1, 70) = 148.79,
Significance (paired) *	$p \leq 0.001$	$p \leq 0.001$		$p < 0.001$
Testosterone: Pre	0.65 (0.56–0.74)	0.51 (0.28–0.72)	$p \leq 0.66$	Group Effect: F (1, 70) = 75.31, $p < 0.001$
Post	0.27 (0.19–0.31)	0.26 (0.20–0.33)	$p \leq 0.001$	Time Effect: F (1, 70) = 305.66, $p < 0.001$
% change	$-$58.5	$-$49.0		Group $\times$ Time Interaction: F (1, 70) = 39.48,
Significance (paired) *	$p \leq 0.001$	$p \leq 0.001$		$p < 0.001$

Table 2. *Cont.*

	HIIT Median (Min–Max)	TRT Median (Min–Max)	Mann–Whitney (Independent Groups)	Aligned Rank Transform (ART)
LH: Pre	4.0 (2–10)	6.0 (3–10)	$p \leq 0.6$	Group Effect: F (1, 70) = 6.48, $p = 0.013$
Post	4.0 (2–10)	6.0 (3–9)	$p \leq 0.2$	Time Effect: F (1, 70) = 1.93, $p = 0.169$
% change	0	0		Group × Time Interaction: F (1, 70) = 3.7,
Significance (paired) *	$p \leq 0.29$	$p \leq 0.97$		$p = 0.056$
FSH: Pre	6.38 (5–7)	6.5 (5–7)	$p \leq 0.39$	Group Effect: F (1, 70) = 2.86, $p = 0.095$
Post	6 (4–6)	6 (4–6)	$p \leq 0.02$	Time Effect: F (1, 70) = 60.1, $p < 0.001$
% change	−6.0	−7.7		Group × Time Interaction: F (1, 70) = 1.87,
Significance (paired) *	$p \leq 0.001$	$p \leq 0.001$		$p = 0.176$
Prolactin: Pre	10 (7–13)	12 (8–13)	$p \leq 0.02$	Group Effect: F (1, 70) = 11.01, $p = 0.0014$
Post	9.5 (6–12)	11.75 (8–13)	$p \leq 0.001$	Time Effect: F (1, 70) = 223.43, $p < 0.001$
% change	−5.0	−2.1		Group × Time Interaction: F (1, 70) = 17.46,
Significance (paired) *	$p \leq 0.001$	$p \leq 0.001$		$p < 0.001$

* Wilcoxon signed ranks test; ART—Aligned Rank Transform; LH—luteinizing hormone; FSH—Follicle-stimulating hormone.

Figure 1 illustrates the principal data from the present study, indicating that the 10-week training regimen considerably influenced levels of estrogen, testosterone, and follicle-stimulating hormone (FSH). Both cohorts exhibited substantial elevations in estrogen levels (HIIT: 150%; TRT: 72.3%) and reductions in testosterone (HIIT: 58%; TRT: 49%) and FSH (HIIT: 6%; TRT: 7.7%).

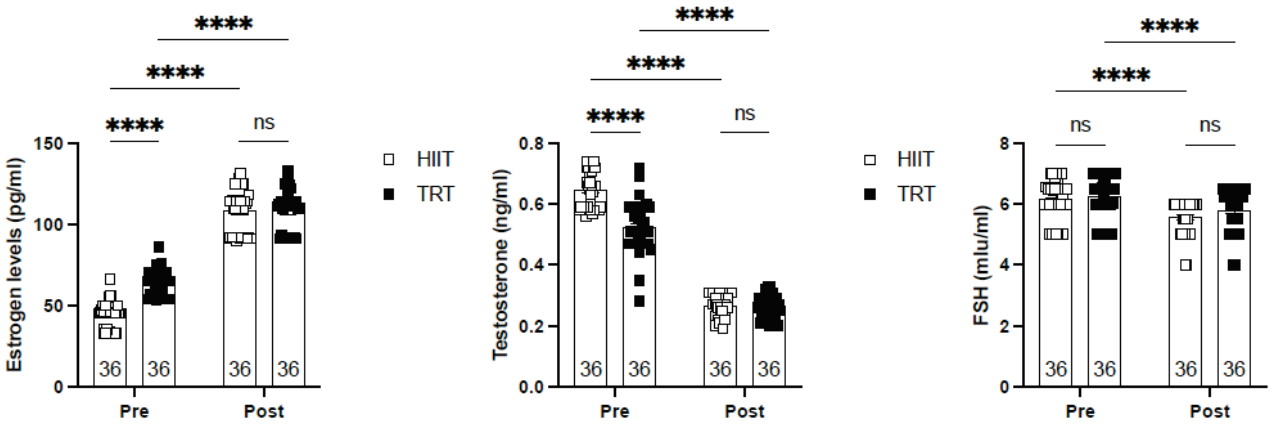


Figure 1. The concentrations of estrogen (pg/mL), testosterone (ng/mL), and follicle-stimulating hormone (FSH) (mIU/mL) under conditions before and after exercise training. **** ($p < 0.0001$), ns (non-significant).

Figure 2 illustrates the concentrations of luteinizing hormone (LH) and prolactin (ng/mL) before and after exercise training. Both experimental groups exhibited significant reductions in prolactin levels, with the HIIT group showing a 5% decrease and the TRT group a 2.1% decrease. No significant alterations were observed in luteinizing hormone levels.

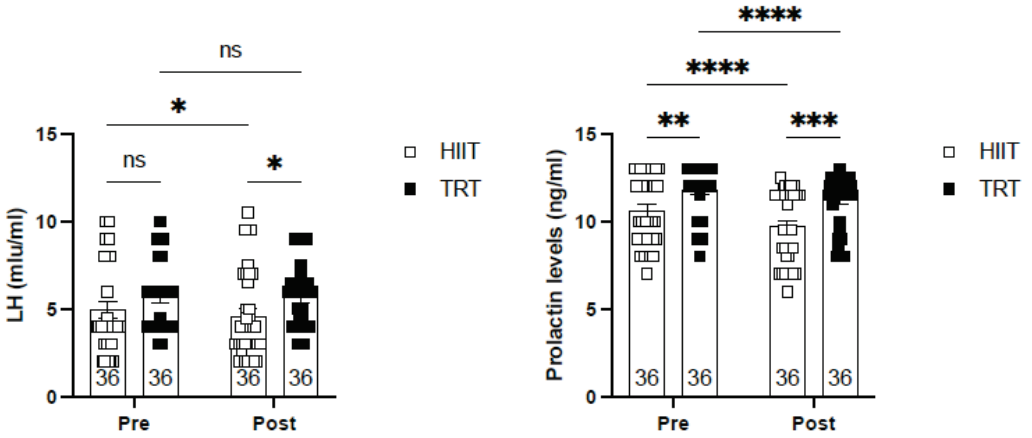


Figure 2. The concentrations of luteinizing hormone (LH) and prolactin (ng/mL) under conditions before and after exercise training. * ($p < 0.05$), ** ($p < 0.01$), *** ($p < 0.001$), **** ($p < 0.0001$), and ns (non-significant).

4. Discussion

Estrogen levels and other sex hormones in women are influenced by various factors, including exercise intensity, duration, menstrual phase, hormonal status, and the timing of post-exercise measurements [5,23]. These variables contribute to the inconsistencies observed in the literature regarding the specific effects of exercise on hormonal profiles. To elucidate the impact of high-intensity interval training (HIIT) on the hormonal profiles of young female individuals, we conducted the present study.

Our study demonstrated a significant increase in estrogen levels, a crucial hormone for the development and functionality of female secondary sexual characteristics and reproductive organs [24]. These findings align with those of Hackney and Willett (2020) [15], who examined the hormonal responses of young women to moderate bicycle ergometer training over eight weeks at a fixed relative intensity. Similarly, Copeland (2002) [25] carried out a study examining the hormonal responses to endurance and resistance exercise in females aged 19 to 69 years. The study found that acute bouts of both endurance and resistance exercise led to significant increases in anabolic hormones, including testosterone, estradiol, and growth hormone. Additionally, dehydroepiandrosterone (DHEA) levels increased significantly following resistance exercise. These findings suggest that exercise can acutely elevate concentrations of anabolic hormones in women across a wide age range [25]. Mannerkorpi et al. (2017) [26] emphasized the effect of physical activity on female hormonal circulation, noting increased estradiol levels following endurance and resistance exercises.

A key finding of our study was the statistically significant increase in estrogen and a significant decrease in testosterone levels. This result contrasts with Gharahdaghi et al. (2021) [14], who reported only a transient elevation in testosterone levels following resistance exercise in young, healthy females. However, a direct comparison of these results is challenging due to differences in exercise stimuli.

Kochańska-Dziurowicz et al. (2001) [24] found that acute exercise on a cycle ergometer led to a significant increase in testosterone levels in young female runners, which returned to baseline 90 min post-exercise. This underscores the importance of timing in determining testosterone levels after exercise.

Conversely, several studies have indicated that exercise does not impact testosterone levels or menstrual cycles in trained young women, suggesting that training status influences hormonal responses. Significant changes in testosterone levels have primarily

been observed with resistance training interventions [27]. This indicates the necessity of different exercise stimuli and extended training durations to induce notable adaptations in testosterone levels. Further research with varied exercise stimuli and longer training periods is needed.

The existing literature suggests that physical activity generally benefits female hormonal profiles, with sex hormone levels often being used to gauge the effectiveness of physical training and to determine appropriate exercise dosages for women. Our study showed that HIIT significantly affected estrogen, testosterone, FSH, and prolactin serum hormone levels in young women, though no significant changes were observed in prolactin (PRL) and luteinizing hormone (LH) levels. The differences observed had large effect sizes (Cohen's d $\geq$ 0.8), indicating practical significance.

Despite the observed increase in estrogen levels, there were no corresponding changes in serum PRL and LH levels. This result, along with the decrease in testosterone, may align with findings from a recent meta-analysis by Ennour-Idrissi et al. (2015) [5], who reported a decrease in total and free estradiol, as well as testosterone, following exercise training, particularly in non-obese individuals and after high-intensity exercise. This decrease was not fully explained by weight loss, highlighting the beneficial role of physical activity for women.

Our analysis indicates that the impact of physical activity on female sex hormones might be relatively minor and not clinically significant. Additionally, measuring sex hormone levels in the blood may not accurately reflect their effects on specific tissues. Physical activity might influence hormone function by altering the sensitivity of target tissues [28]. Estrogen secretion is regulated through a complex feedback system involving the hypothalamus, pituitary gland, and ovaries. Gonadotropin-releasing hormone (GnRH) from the hypothalamus stimulates the pituitary to release FSH and LH, which, in turn, stimulate ovarian follicles to produce estrogen. Elevated estrogen levels then inhibit GnRH and FSH release through negative feedback to regulate estrogen production [29]. Our study found increased estrogen levels despite decreased FSH after 11 weeks of HIIT in young females.

Generally, exercise tends to reduce estrogen levels, while estrogen metabolites remain unchanged [30]. However, the relationship between physical exercise and hormone levels in women remains complex. Regular exercise has been associated with reduced circulating estrogen levels [31]. It is important to consider that factors such as under-recovery and inadequate nutritional intake may also significantly affect hormone regulation. Moderate-intensity resistance training and cardiovascular exercise are linked to beneficial effects on hormones, including testosterone and progesterone, while intense exercise without proper recovery and nutrition can lead to reduced estrogen levels. A low-protein diet is associated with hormonal imbalances, including low estrogen levels [32].

5. Conclusions

This study demonstrates that HIIT and TRT can lead to alterations in the levels of reproductive hormones in females. Post-training assessments indicated a significant increase in estrogen levels, with values of (45 ± 33 vs. 112.5 ± 41) (pg/mL) in the HIIT group, and (65 ± 33 vs. 112 ± 42) (pg/mL) in the TRT group, respectively (p-value < 0.001). Conversely, testosterone levels demonstrated a significant decrease from pre- to post-training, recording values of (0.65 ± 0.18 vs. 0.27 ± 0.12) (ng/mL) in the HIIT group, and (0.51 ± 0.44 vs. 0.26 ± 0.13) (ng/mL) in the TRT group, respectively. Consequently, individuals seeking enhancements in overall fitness should consider incorporating HIIT and TRT into their training regimens. The clinical implication is that both HIIT and TRT

are effective in modulating key hormonal levels, with potential applications in fitness programming for young women.

Given the hormonal adaptations described above, it is advisable for fitness professionals to incorporate HIIT and TRT protocols into training programs for female clients, with careful monitoring of individual responses to optimize endocrine health. Additionally, considering the potential impact of the menstrual cycle on training outcomes, aligning exercise regimens with different phases may enhance performance and recovery [32].

Future research should investigate long-term hormonal responses to combined HIIT and TRT protocols and their effects on menstrual and reproductive health, as well as metabolic outcomes.

Author Contributions: W.R. and C.E.X. conceptualized and designed the study and drafted the initial manuscript. W.R. and A.-H.E.-G. provided critical feedback, comments, suggestions, and significant inputs. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The institutional research board (IRB) of the Faculty of Physical Education, Mansoura University, approved this study (code: 1175, approval date: 22 November 2022).

Informed Consent Statement: This study complied with the Declaration of Helsinki, as well as Ethical Standards in the research of exercise and sports. Informed written consent was obtained from all participants in our study.

Data Availability Statement: The datasets employed in this study can be obtained from the corresponding author upon reasonable request. However, certain data cannot be made publicly accessible due to privacy considerations.

Acknowledgments: We express our gratitude to the participants, who facilitated the execution of this study.

Conflicts of Interest: The authors declare that they have no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

HIIT	High-intensity interval training
TRT	Traditional resistance training
FSH	Follicle-stimulating hormone
LH	luteinizing hormone

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Six Weeks of Boxing Training Lowers Blood Pressure and Improves Vascular Function in Young Men and Women with Elevated Blood Pressure or Stage 1 Hypertension†

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Abstract

(1) Background: Early stages of hypertension, including elevated blood pressure and stage 1 hypertension, are known to increase cardiovascular risk and mortality. Exercise is widely recommended for blood pressure management; however, the optimal exercise modality and the underlying vascular mechanisms remain uncertain. (2) Methods: This study investigated the effects of boxing training on clinical and vascular parameters in young adults with elevated blood pressure or stage 1 hypertension. Twenty-four participants (mean age 25.4 ± 4.9 years) were randomly assigned to a boxing training group or a control group. Over six weeks, the intervention group performed boxing training three times per week, consisting of ten three-minute rounds interspersed with one-minute rests, while controls completed flexibility and balance exercises. (3) Results: Boxing training produced significant group-by-time interactions for peripheral and central blood pressure, endothelial function, and carotid artery structure. Reductions were observed in systolic (~16 mmHg) and diastolic (~10 mmHg) blood pressure and in central systolic pressure (~mmHg). Vascular function improved, as indicated by greater brachial and popliteal flow-mediated dilation and increased forearm and calf blood flow, accompanied by enhanced nitric oxide bioavailability and reduced inflammation. (4) Conclusions: These findings suggest that boxing training is an effective and time-efficient exercise modality for improving vascular health and managing early hypertension in young adults.

Keywords: boxing training; high blood pressure; endothelial function

1. Introduction

Cardiovascular diseases (CVD), such as coronary artery disease, heart failure, peripheral artery disease, and stroke, are responsible for 17.3 million annual deaths, which account for a third of all global causes of death [1]. High blood pressure is the most prevalent risk

factor for the development of CVD and represents the primary cause of global morbidity and mortality [2]. Even early stages of high blood pressure, such as elevated blood pressure or stage 1 hypertension, have been shown to increase cardiovascular mortality [3].

While physical inactivity is a significant contributor, the etiology of hypertension is complex and multifactorial, involving lifestyle factors such as poor diet, excessive body mass index (BMI), high visceral adiposity, and the chronic effects of stress or poor sleep hygiene. Several pathological features are involved and interconnected in the development of high blood pressure, such as endothelial dysfunction, oxidative stress, inflammation, autonomic dysfunction, an overreactive renin–angiotensin–aldosterone pathway, and arterial stiffness [4]. Endothelial dysfunction appears to have a central role in the progression to high blood pressure according to the Mosaic Theory, mainly by affecting the ability of the vessels to maintain homeostasis [5]. Endothelial dysfunction can be identified by one or more of the following characteristics: (1) a decline in nitric oxide (NO) bioavailability and subsequent impaired vasodilation, (2) upregulation of adhesion molecules and inflammatory genes, (3) oxidant stress exacerbation, and (4) increased permeability of the endothelial barrier [6]. Meanwhile, arterial stiffness directly impacts blood pressure by affecting afterload and arterial–ventricular coupling [7,8].

Individuals with elevated blood pressure or stage 1 hypertension without an estimated 10-year risk of CVD of $\geq$10%, as calculated by the American College of Cardiology/American Heart Association (ACC/AHA) Pooled Cohort Equations, are not candidates for drug treatment. In turn, management strategies for this population primarily include lifestyle modifications, such as the incorporation of an exercise training program [9]. Current medical guidelines have established that exercise is a cornerstone in high blood pressure prevention and treatment, and its effectiveness is comparable to drug treatment [9,10]. Indeed, for every dollar invested in strategies to incorporate physical activity as a preventive cardiovascular tool, there is a return of approximately three to six dollars in terms of healthcare costs [1]. However, the optimal exercise prescription dose and exercise modality for high blood pressure and the mechanisms behind the health benefits of exercise have not yet been fully clarified [11].

Boxing training is a type of exercise that involves high cardiovascular demands, high-impact punching, and coordinated movements in an enjoyable environment. It is characterized by alternating periods of intense physical effort (e.g., striking drills, footwork) and brief, active recovery periods. This interval nature demands significant and rapid engagement of both the circulatory and respiratory systems, which may be a potent stimulus for inducing central and peripheral cardiovascular adaptations [12,13]. Previously, boxing training has been shown to have excellent motor outcomes in stroke [14] and Parkinson's disease patients [15]. Nonetheless, research regarding the effects of boxing training on cardiovascular health is scarce. To date, no randomized controlled trial employing boxing training as an intervention for individuals with high blood pressure has been conducted. Therefore, this study aims to determine the effects of boxing training on clinical and vascular health in individuals with elevated blood pressure or stage 1 hypertension. We hypothesized that six weeks of high-intensity boxing training would lead to significant reductions in both peripheral and central blood pressure, alongside improvements in endothelial function, arterial stiffness, and inflammation, compared to a non-exercise control group.

2. Materials and Methods

2.1. Participants

Participants were recruited from the University of Texas at El Paso and its surroundings. A preliminary blood pressure screening and a health questionnaire identified them. The cohort

https://doi.org/10.3390/sports14010005

consisted of subjects who met the following inclusion criteria: (1) ≥18 years old, (2) systolic blood pressure (SBP) between 120 and 139 mmHg and/or diastolic blood pressure (DBP) between 80 and 89 mmHg obtained from 2 different days, (3) an estimated 10-year risk of CVD ≤ 10%, calculated by the ACC/AHA Pooled Cohort Equations, and (4) no current participation in 3 or more days per week of endurance or resistance exercise training. Exclusion criteria included non-controlled cardiac, pulmonary, or metabolic diseases, smoking, consumption of nutritional supplements containing antioxidants, and any physical impairment to exercise. All participants signed a written informed consent. The study protocol was approved by the local ethics committee (UTEP IRB Study Number 1364179-3).

2.2. Protocol

The study was a double-blind (both evaluator and participant), randomized, controlled trial (ClinicalTrials.gov ID NCT06413251). An initial brachial blood pressure screening was performed to identify potential participants for the present study. Those with SBP readings between 120 and 139 mmHg or DBP between 80 and 89 mmHg were instructed to report to the Clinical Applied Physiology Lab at the University of Texas at El Paso for a second blood pressure assessment to confirm the diagnosis of elevated blood pressure or stage 1 hypertension. Then, participants were asked to complete a health questionnaire to rule out any cardiac, pulmonary, or metabolic conditions. Once they were cleared to participate, participants started the informed consent process. After obtaining the consent, their height and weight were measured using a stadiometer (Seca 225, Seca Medical Measuring Systems and Scales, Hamburg, Germany) and a digital scale (Tanita WB-110A, Tanita Corporation, Tokyo, Japan). Thereafter, participants were asked to lie down in supine position over an examination table for 10 min, where carotid–femoral tonometry (Sphygmocor, Xcel, West Ryde, Australia), carotid, brachial, and popliteal ultrasound imaging (MyLab30 Gold Cardiovascular, Esaote, Firenze, Italy), and strain gauge venous occlusion plethysmography (AI6 Arterial Inflow System, D.E. Hokanson Inc., Bellevue, WA, USA) were performed from the right side of their body. At the end of the lab visit, blood samples were collected from the antecubital vein of the participants. All vascular measurements were conducted under strictly standardized conditions in a climate-controlled room (22–24 °C). Participants reported to the laboratory in the morning (7:00 a.m.–12:00 p.m.) after a 12 h overnight fast and were instructed to abstain from alcohol, caffeine, and vigorous exercise for at least 24 h prior to the assessment.

Participants were then randomly assigned by a member of the research team (L.R.), who was not involved in the assessments or the analysis, into a boxing or a control group using an online number generator (https://www.graphpad.com/quickcalcs/randomize1/ accessed on 20 August 2019). Participants were unaware of the allocation possibilities. A 6-week intervention was designed for each group at the Clinical Applied Physiology Lab at the University of Texas at El Paso. Each intervention was supervised by members of the research team who were not involved in the assessments or the analysis (M.G. and P.C.). Finally, all the measurements taken in the first lab visit were repeated in the same order at the end of the intervention. The evaluator (F.M.A.) who performed the pre- and post-assessments was blinded to the allocation of each participant.

2.3. Measurements

2.3.1. Brachial Blood Pressure

Blood pressure assessments were performed according to the ACC/AHA recommendations [9]. Briefly, participants were seated in a chair for five minutes with their feet on the floor and their back supported, followed by an attended recording of blood pressure in trip-

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licate with a validated automated brachial blood pressure cuff (BP760, Omron Healthcare, Inc., Lake Forest, IL, USA).

2.3.2. Central Blood Pressure

A cuff-based device for PWA (Sphygmocor Xcel, AtCor Medical, West Ryde, Australia) was attached to the right arm of every participant in a supine position after 10 min of resting. Each PWA assessment lasted between 60 and 120 s: 50–110 s to record brachial blood pressure and 10 s of sub-diastolic recordings. Central blood pressure waveforms were generated by a validated transfer function [16]. According to the manufacturer's recommendations, the blood pressure waveforms were considered acceptable if the overall quality control indices were equal to or above 75%. The following PWA variables were assessed: central systolic blood pressure (cSBP), central diastolic blood pressure (cDBP), central pulse pressure (cPP), augmentation index (AIx), and augmentation index normalized to a heart rate of 75 bpm (AIx@75). cSBP and cDBP are the estimated blood pressures at the ascending aortic wall during systole and diastole, respectively. cPP is the difference between cSBP and cDBP. AIx is the ratio between the increase in aortic blood pressure produced by reflected waves in relation to cPP, and AIX@75 is the normalization of AIx to 75 bpm [17]. All these variables have been associated with cardiovascular risk [18]. Additionally, Wasted Left Ventricular Energy (LVE_W), a surrogate for left ventricle work and myocardial oxygen demand, was estimated from the pulse pressure curve and the duration of the reflected wave. LVE_W was calculated using the following formula: $LVE_W = ((ED - \Delta t_p) \times (cSBP - Pi)\, \pi/4) \times 1.33322$, where ED is ejection duration, Δt_p is time to arrival of the reflected pressure wave, and Pi is the pressure at the first inflection point marking the onset of the reflected aortic pressure wave [19,20].

2.3.3. Pulse Wave Velocity

Carotid–femoral pulse wave velocity (PWVcf) is considered the gold standard to determine arterial stiffness [21]. For this procedure, participants were supine over an examination table for 10 min, and a cuff was placed on the right thigh. During this period, carotid and femoral pulses were palpated. Then the following distances were measured using a metallic tape: carotid to sternal notch, sternal notch to cuff, and femoral to cuff. Once the participant reached hemodynamic stability, a high-fidelity tonometer was placed over the carotid artery. Pulse waves of the carotid and femoral arteries were simultaneously recorded by the tonometer and the cuff, respectively. PWVcf was determined by dividing the distance obtained through the subtractive method by the delay time between waves [22–25].

2.3.4. Flow-Mediated Dilation

Flow-mediated dilation (FMD) is considered a surrogate of endothelial function. For brachial FMD, participants were asked to lie down in a supine position over an examination table for at least 10 min. A total of six electrodes were attached to their chest in the standard lead II setting, where three electrodes were connected to a high-definition ultrasound machine (MyLab30 Gold Cardiovascular, Esaote, Firenze, Italy) and the other three were connected to an electrocardiogram trigger system (MP150WSW, BIOPAC Systems Inc., Goleta, CA, USA and Frame Grabbing and Digital Data Input modules, Medical Imaging Applications LLC, Coralville, IA, USA). The right arm was moved at 80–90° of shoulder abduction over an armrest, and a blood pressure cuff was attached to the forearm just below the antecubital fossa. A 12 MHz linear phase array ultrasound transducer (LA435, Esaote, Firenze, Italy) with a transducer holder (Patent US20200155117A1) was placed 5 cm above the antecubital fossa to image the right brachial artery according to international

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guidelines for FMD [26–28]. Basal artery diameters and peak systolic blood flow velocities were recorded in basal conditions at every QRS complex captured by the electrocardiogram trigger system using an automated edge-detection software (Vascular Research Tools, version 5, Medical Imaging Applications LLC, IA, USA) for 30 s. Then, the forearm cuff was inflated to supra-systolic pressure (>200 mmHg) for 5 min, followed by the deflation of the cuff. Brachial artery diameters and blood flow velocities were continuously registered every 3 s for 150 s, starting at 30 s before deflation until 2 min after deflation using the automated edge-detection software. Peak diameters were identified as the single peak diameter observed during the plateau phase after cuff deflation [29]. The reliability of FMD analysis in our lab has already been tested and is described elsewhere [30]. For popliteal FMD, the same procedure is repeated, but with the difference that the cuff and the transducer are placed in the leg and in the popliteal fossa, respectively. FMD was calculated as FMD% = 100 × (peak diameter − basal diameter)/basal diameter [31].

2.3.5. Forearm and Calf Blood Flow

Forearm blood flow (FBF) and calf blood flow (CBF) were assessed by strain gauge venous occlusion plethysmography (AI6 Arterial Inflow System, D.E. Hokanson Inc., Bellevue, WA, USA). Participants were in a supine position over an examination table where strain gauges were placed at the widest part of the right forearm or calf. Next, an upper-arm cuff for FBF and a thigh cuff for CBF were cycled from 0 to 50 mmHg for seven seconds every 15 s to prevent venous outflow. One minute before each measurement, a wrist and an ankle cuff were inflated to 200 mmHg to occlude hand and ankle circulation, respectively. Absolute blood flow was determined by the rate of change in limb circumference (e.g., slope) during the seven-second venous occlusion. FBF and CBF were estimated as the average of three readings in a minute [32].

2.3.6. Forearm and Calf Blood Flow During Reactive Hyperemia

FBF and CBF during reactive hyperemia were measured after five minutes of occlusion of the arm or thigh, respectively. These measurements are a reliable non-invasive alternative to estimate endothelial function in resistance vessels [33]. Baseline FBF and CBF were recorded for 2 min, then the respective cuff was inflated to 200 mmHg for five minutes and then rapidly deflated. FBF and CBF were measured every 15 s for three minutes. Peak FBF and CBF were selected from the highest value of blood flow following deflation of the cuff [32].

2.3.7. Carotid Artery Ultrasound

An 8–18 Hz ultrasound transducer (LA435, Esaote, Firenze, Italy) inserted into a neck transducer holder was attached to the right side of the neck of each participant, and the mid-section of the common coronary artery was identified in a high-definition ultrasound machine (MyLab30 Gold Cardiovascular, Esaote, Firenze, Italy). Resting arterial diameters and peak systolic blood flow velocities were recorded continuously for 10 s at a rate of 10 frames per second using an automated edge-detection software (Vascular Research Tools, Version 5, Medical Imaging Applications LLC, Coralville, IA, USA).

2.3.8. Endothelial Shear Stress Estimations

Resting endothelial shear stress (ESS) of each artery was estimated during 10 seconds by Womersley's approximation, using ESS = $\mu \times SR$ and $SR = 2K \times V/D$, where μ is blood viscosity, SR is shear rate, V is peak systolic velocity, D is artery diameter, K is a complex factor dependent only on the Womersley parameter (α), and $\alpha = (D/2) \times (\omega/(\mu/\rho))^{1/2}$, where ω is the angular frequency of the flow pulsation ($\omega = freq \times 2\pi$), ρ is blood density,

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and μ is blood viscosity [34,35]. ESS is expressed in dynes/cm^2. Blood viscosity and density were calculated using the following formulas [36–38]: $\mu_{plasma} = \frac{\exp\left[-5.64+\frac{1800}{T+273}\right]}{SR}$, $\mu = \mu_{plasma} \times \exp(2.31HCT)$, and $\rho = [1.09HCT + 1.035 \times (1 - HCT)]$, where μ_{plasma} is plasma dynamic viscosity expressed in Pa·s, T is temperature expressed in °C, and Hct is Hematocrit expressed as a fraction.

2.3.9. Antecubital Vein Blood Collection

After 48 h of a low-nitrate diet under fasting conditions, 20 mL blood samples were obtained from the antecubital vein of each participant. Blood samples were immediately centrifuged to obtain plasma samples, with the latter being placed in aliquots at −80 °C until analysis. NOx (Total Nitric Oxide and Nitrate/Nitrite Parameter Assay Kit, R&D Systems, Minneapolis, MN, USA), lipid profile (HDL and LDL/VLDL Cholesterol Assay Kit, ab65390, Abcam, Cambridge, UK), CRP (C-Reactive Protein (human) ELISA Kit, 10011236, Cayman, Ann Arbor, MI, USA), IL-6 (Interleukin-6 (human) ELISA Kit, 501030, Cayman), TNF-α (TNF-α (human) ELISA Kit, 589201, Cayman), F2-isoprostanes (STAT-8-isoprostane ELISA Kit, 500431, Cayman), TAC (Antioxidant Assay Kit, 709001, Cayman), and SOD (Superoxide Dismutase Assay Kit, 706002, Cayman) were performed according to the manufacturer's instructions for their respective kit at the core lab of the health sciences building at UTEP.

2.4. Interventions

2.4.1. Boxing Training

First, during a familiarization visit, participants learned how to wrap their hands and perform basic boxing techniques, such as stance and punches, while wearing 14-oz gloves. This visit finished with an incremental boxing test that consisted of punching a 100 lb heavy bag (Ringside soft-filled leather, Ringside-CSI Fitness 1st, Lenexa, KS, USA) at a fixed force (~20 kg) and with an increase in the punching cadence every 2 min. The force was tracked by a sensor attached to the bottom of the heavy bag (UFC Force Tracker), which, via a phone app (XFORCE tracker, SEROSE), gave visual feedback of power and rhythm to the participant. The test started at a cadence of 140 punches per minute (ppm) controlled by a metronome (Pro Metronome by EUMLab, Xanin Tech. GmbH., Berlin, Germany) and was increased by 30 ppm every 2 min until fatigue. Fatigue was determined when participants were unable to maintain the punching tempo, and they were asked to perform a 1 min all-out effort to finish the test. Oxygen uptake (VO_2) was measured during a subsample of sessions via indirect calorimetry using a portable metabolic cart (Parvomedics Inc., Sandy, UT, USA) at the end of each 2 min workload. Heart Rate (HR) was monitored continuously with a chest strap monitor (Polar H9). Rate of Perceived Exertion (RPE) was assessed immediately following each round using the 0–10 Modified Borg Scale.

The boxing training intervention consisted of three exercise sessions per week on non-consecutive days for six weeks. All boxing training sessions were conducted at the Clinical Applied Physiology Lab, University of Texas at El Paso. Training sessions were individualized and were instructed by at least 2 lab members with a bachelor's degree in kinesiology and experience in boxing training to ensure safety, proper technique, and adherence to the high-intensity interval protocol. The workout began with a 3 min warm-up period where participants actively moved their shoulders, elbows, wrists, and finger joints. Participants were then instructed to complete 10 rounds of three minutes with a one-minute resting period interspersed. During the rounds, participants punched a heavy bag (e.g., straight, jab, hook) or did mitt work. The intensity of the first 3 rounds was set at 90–95% VO_2max and at approximately 95% heart rate reserve (HRR), which was above their individual ventilatory threshold 2. The intensity of the remaining seven rounds was set just below their first ventila-

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tory threshold at approximately 60% of HRR or less than 4 on the modified RPE scale (1–10). The exercise intensity was deliberately tapered after the initial three high-intensity rounds (targeting 95% of HRR) to incorporate an active recovery and to manage accumulated fatigue. This varied intensity structure was implemented to improve exercise adherence over the six-week program and reduce the risk of overtraining. The final rounds were maintained at a moderate-intensity level (targeting 60% HRR), which is sufficient to sustain metabolic activity while promoting recovery. Heart rate and RPE were constantly monitored to ensure that each participant was exercising at the desired intensity. Training progression was adjusted weekly by increasing the punching cadence to maintain the target 95% HRR for the first three rounds and an RPE just below 4 for the remaining rounds.

2.4.2. Flexibility and Balance Training (Control)

The control group performed 10 min of dynamic articular movement, 5 min of unipedal stance, and 5 min of stretching of the upper limbs three days per week for six weeks.

2.5. Statistical Analysis

Data was analyzed using SPSS version 24.0. Graphs were elaborated using GraphPad Prism 10.3.1. Normal distribution of the data was examined with the Shapiro–Wilk test and visual inspection. Independent *t*-tests were conducted to compare demographic variables between groups. A repeated measure general linear model (GLM) with two levels of time (pre and post) and using two groups (Boxing and Control) was employed to compare between-group and within-group differences. Fisher's Least Significant Difference (LSD) was selected as the post hoc test and partial eta-squared effect size (η_p^2) as the indicator of effect size. η_p^2 of 0.02, 0.13, and 0.26 were considered small, medium, and large effects, respectively [39]. To evaluate whether sex or adiposity could confound the effects of the intervention, we conducted correlation analyses examining the associations between sex, baseline body mass index (BMI), changes in BMI (ΔBMI), and hemodynamic, vascular, and biochemical responses. Baseline BMI was calculated using measured height and pre-intervention body mass. Pearson correlation coefficients (r) and corresponding *p*-values were computed for each predictor–outcome pair. Significance was established at $\alpha \leq 0.05$. The sample size was determined using the software G*Power 3.1. Based on Izadi et al.'s [40] results on the effects of six weeks of HIIT on SBP (effect size = 1.73), establishing α at 0.05 and β at 0.2, and assuming a 30% dropout rate, the estimated number of participants per group was 12.

3. Results

Initially, 38 individuals were assessed for eligibility in a time frame of approximately 3 months. Fourteen subjects were excluded because their blood pressure did not meet the inclusion criteria. As Figure 1 exhibits, a total of 24 participants were randomly allocated to one of the two groups. Only 1 participant was lost to follow-up assessments in the control group, leaving 12 participants in the boxing group and 11 participants in the control group that were finally analyzed. All analyzed participants were college students.

All variables were normally distributed except for age. All data is presented as mean and standard deviation, unless otherwise stated. The baseline demographic characteristics of both groups are summarized in Table 1. No difference was found between groups regarding age (U = 86.0, $p = 0.235$), height (t(21) = 0.39, $p = 0.698$), weight (t(21) = 0.78, $p = 0.442$), hematocrit (t(21) = −0.06, $p = 0.953$), SBP (t(21) = −0.98, $p = 0.339$), and DBP (t(21) = −0.301, $p = 0.766$) before the intervention.

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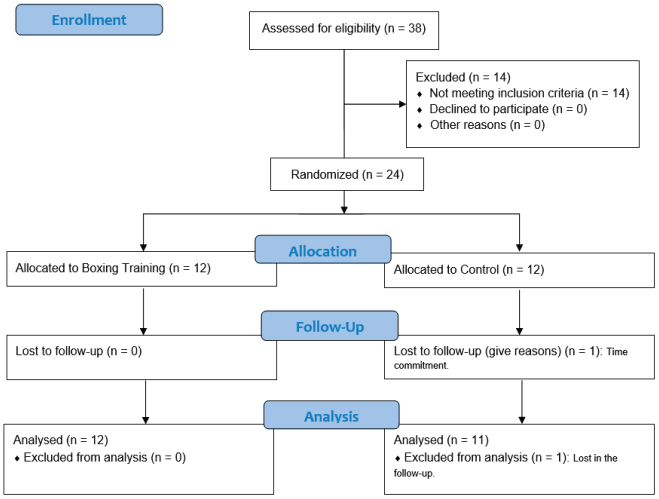


Figure 1. Flow chart of participants.

Table 1. Demographic characteristics of the participants.

	Boxing Training Group			Control Group			
	Male $n = 8$	**Female** $n = 4$	**Total** N = 12	**Male** $n = 7$	**Female** $n = 4$	**Total** N = 11	p
Age (y)	27.6 (6.7)	23.5 (0.6)	26.3 (5.7)	26.0 (4.9)	22.0 (0.8)	24.6 (4.3)	0.235
Height (m)	1.7 (0.1)	1.5 (0.1)	1.7 (0.1)	1.7 (0.1)	1.6 (0.1)	1.7 (0.1)	0.698
Weight (kg)	97.7 (24.9)	72.4 (17.9)	89.3 (25.2)	100.6 (17.9)	88.8 (11.7)	96.3 (16.4)	0.442
Hct (%)	49.3 (3.4)	46.0 (3.3)	48.0 (3.7)	49.0 (2.9)	46.0 (4.2)	47.9 (3.5)	0.953
SBP (mmHg)	130.0 (7.2)	113.3 (4.6)	124.4 (10.3)	124.7 (13.3)	110.0 (11.8)	119.4 (14.3)	0.339
DBP (mmHg)	84.9 (6.1)	83.8 (2.5)	84.5 (5.1)	83.9 (4.7)	84.0 (4.1)	83.9 (4.2)	0.766

Data expressed as mean (SD). Hct: Hematocrit; SBP: systolic blood pressure; DBP: diastolic blood pressure.

Compliance with the boxing training protocol was 98.1% ± 3.9%. Overall, 95.4% of the target heart rates were sustained during the three high-intensity rounds. Furthermore, they kept their heart rate within the required range for low intensity or recovery in all (100%) of the measurements taken during the remaining 7 rounds. Additionally, participants reported a mean RPE of 8.3 and 2.8 for the high-intensity and low-intensity rounds, respectively. Meanwhile, the compliance with the flexibility and balance training was 27.3% ± 13.4% in the control group. No adverse cardiovascular effects were reported throughout the intervention. Only 3 participants experienced anterior shoulder tenderness when punching during the first week of training, which was relieved in the subsequent weeks.

3.1. Peripheral Blood Pressure

Significant interactions were observed for SBP ($F(1,21) = 32.34$, $p < 0.001$) and DBP ($F(1,21) = 39.54$, $p < 0.001$). No differences were observed in SBP ($F(1,21) = 0.96$, $p = 0.339$) and DBP ($F(1,21) = 0.09$, $p = 0.766$) between groups at baseline. Six weeks of boxing training largely decreased systolic blood pressure ($F(1,21) = 48.89$, $p < 0.001$, $\eta_p^2 = 0.700$) and diastolic blood pressure ($F(1,21) = 78.48$, $p < 0.001$, $\eta_p^2 = 0.789$) in individuals with elevated blood pressure and stage 1 hypertension (Figure 2 and Table 2).

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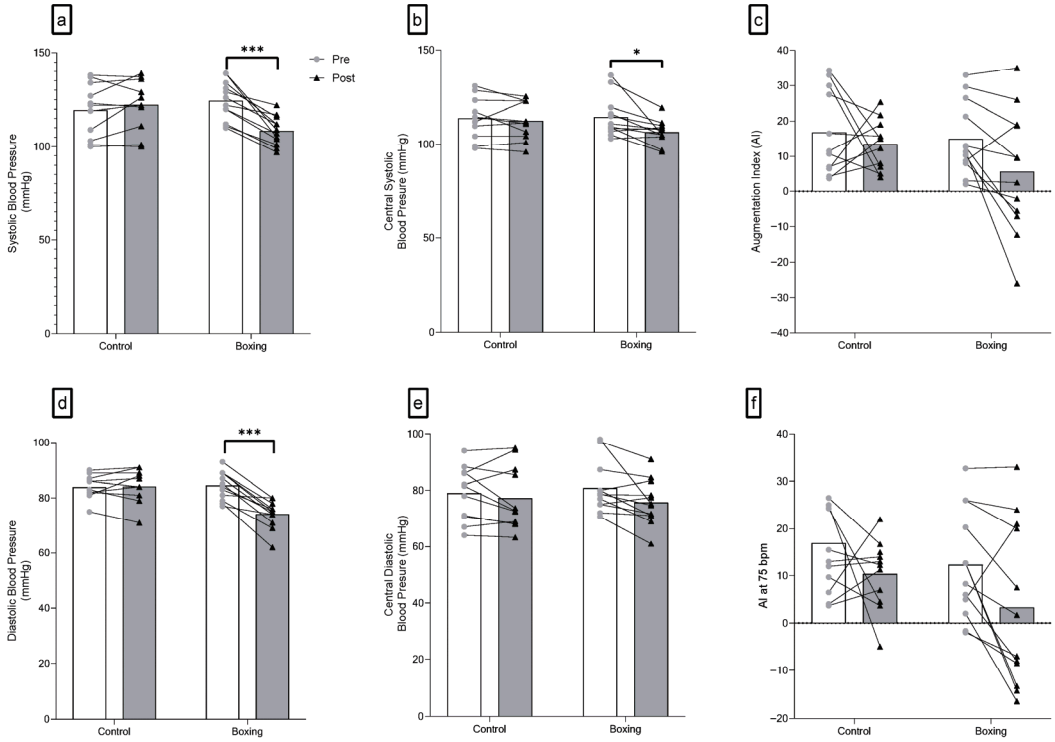


Figure 2. Peripheral (**a**,**d**) and central blood pressure (**b**,**c**,**e**,**f**) changes following 6 weeks of boxing training in individuals with elevated blood pressure or stage 1 hypertension. Augmentation Index (AI) represents the central aortic pressure waveform, showcasing hoy a reflected pulse wave adds to the forward wave. *** $p < 0.001$; * $p < 0.05$.

Table 2. Pulse wave analysis and arterial stiffness changes following 6 weeks of intervention.

	Boxing Training			Control			Interaction	Group	Time
	Before	**After**	**Δ**	**Before**	**After**	**Δ**	***p***	***p***	***p***
SBP (mmHg)	124.4 (10.3)	108.4 (7.7)	−16.0 (8.7)	119.4 (14.3)	122.2 (13.5)	2.8 (7.0)	<0.001	0.351	0.001
DBP (mmHg)	84.5 (5.1)	74.2 (5.0)	−10.3 (4.6)	83.9 (4.3)	84.2 (6.0)	0.3 (3.3)	<0.001	0.026	<0.001
cSBP (mmHg)	114.5 (10.7)	106.5 (6.3)	−7.9 (9.0)	113.9 (11.0)	112.5 (10.0)	−1.4 (5.6)	0.050	0.476	0.008
cDBP (mmHg)	80.8 (9.0)	75.7 (8.0)	−5.1 (7.0)	79.0 (9.7)	77.2 (11.2)	−1.8 (6.0)	0.231	0.972	0.020
cPP (mmHg)	33.6 (4.1)	31.0 (3.6)	−2.8 (3.8)	34.8 (3.3)	33.8 (7.1)	−1.0 (7.3)	0.479	0.207	0.129
AIx (%)	15.0 (10.3)	5.6 (17.4)	−9.3 (12.7)	16.8 (12.1)	13.5 (7.0)	−3.4 (15.0)	0.314	0.271	0.040
AIx@75 (%)	12.3 (11.6)	3.3 (17.3)	−9.0 (11.8)	16.9 (12.7)	10.4 (7.4)	−6.5 (14.9)	0.658	0.213	0.011
LVE_W (dynes/s/cm^2)	1217.5 (509.1)	764.9 (606.1)	−452.7 (351.5)	1422.0 (607.5)	1132.6 (415.0)	−289.4 (747.6)	0.504	0.150	0.006
PWV *cf* (m/s)	6.7 (1.3)	6.5 (1.2)	−0.2 (0.4)	6.4 (1.5)	6.5 (1.2)	0.2 (0.7)	0.096	0.797	0.779

Data expressed as mean (SD). SBP: systolic blood pressure; DBP: diastolic blood pressure; cSBP: central systolic blood pressure; cDBP: central diastolic blood pressure; cPP: pulse pressure; AIx: augmentation index; AIx@75: augmentation index at 75 beats per minute; LVEW: left ventricular energy wasted; PWVcf: pulse wave velocity carotid–femoral.

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3.2. Pulse Wave Analysis

Significant group-by-time interactions were only observed for cSBP (F(1,21) = 4.29, $p = 0.05$). Meanwhile, there were no significant interactions for cDBP (F(1,21) = 1.52, $p = 0.231$), cPP (F(1,21) = 0.52, $p = 0.479$), AIx (F(1,21) = 1.06, $p = 0.314$), AIx@75 (F(1,21) = 0.20, $p = 0.658$), and LVE_w (F(1,21) = 0.46, $p = 0.504$). A large reduction in cSBP (F(1,21) = 13.15, $p = 0.002$, $\eta_p^2 = 0.385$) was observed in the boxing training group following the intervention. Additionally, no significant group-by-time interaction was detected in the duration of the reflected wave (F(1,21) = 2.99, $p = 0.098$) (Figure 2 and Table 2).

3.3. Arterial Stiffness

There was no significant group-by-time interaction for PWVcf (F(1,21) = 0.30, $p = 0.096$) (Table 2).

3.4. Vascular Adaptations

There was a significant group-by-time interaction for brachial FMD (F(1,21) = 22.46, $p < 0.001$). No differences were observed in brachial artery diameter (F(1,21) = 0.33, $p = 0.573$), resting brachial ESS (F(1,21) < 0.01, $p = 0.967$), and brachial FMD (F(1,21) = 0.03, $p = 0.858$) between groups at baseline. Six weeks of boxing training largely increased brachial FMD (F(1,21) = 23.58, $p < 0.001$, $\eta_p^2 = 0.529$) in individuals with elevated blood pressure or stage 1 hypertension. There were no significant group-by-time interactions for brachial artery diameter (F(1,21) = 3.05, $p = 0.095$) and resting brachial ESS (F(1,21) = 0.75, $p = 0.398$) (Figure 3 and Table 3).

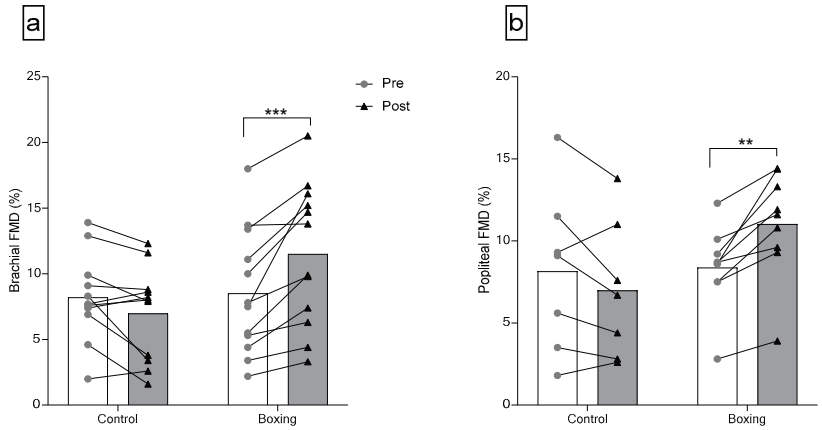


Figure 3. Brachial (**a**) and Popliteal (**b**) Endothelial Function after 6 weeks of boxing training in individuals with elevated blood pressure or stage 1 hypertension. FMD: flow-mediated dilation. *** $p < 0.001$; ** $p < 0.01$.

Significant group-by-time interactions were observed for popliteal artery diameter (F(1,14) = 7.74, $p = 0.015$) and popliteal FMD (F(1,14) = 18.39, $p = 0.001$). No differences were observed in popliteal artery diameter (F(1,14) = 3.90, $p = 0.068$), resting popliteal ESS (F(1,14) = 1.35, $p = 0.264$), and popliteal FMD (F(1,14) = 0.03, $p = 0.858$) between groups at baseline. Six weeks of boxing training induced a large increase in popliteal artery FMD (F(1,14) = 20.19, $p = 0.001$, $\eta_p^2 = 0.591$) and popliteal artery diameter (F(1,14) = 7.53, $p = 0.016$, $\eta_p^2 = 0.350$). There was no group-by-time interaction for resting popliteal ESS (F(1,14) = 0.92, $p = 0.354$) (Figure 3 and Table 3).

There was a significant group-by-time interaction for carotid artery diameter (F(1,21) = 13.44, $p = 0.001$). No differences were observed in carotid artery diameter (F(1,21) = 3.43, $p = 0.078$) and resting carotid ESS (F(1,21) = 0.10, $p = 0.750$) between groups

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at baseline. A significant increase in carotid artery diameter (F(1,21) = 11.68, p = 0.003, η_p^2 = 0.357) was observed in the boxing group at the end of the intervention. There was no group-by-time interaction for resting carotid ESS (F(1,21) = 1.55, p = 0.228) (Table 3).

Table 3. Vascular changes following 6 weeks of intervention.

	Boxing Training			Control			Interaction	Group	Time
	Before	**After**	**Δ**	**Before**	**After**	**Δ**	***p***	***p***	***p***
Brachial Diameter (mm)	3.7 (0.6)	3.8 (0.7)	0.1 (0.2)	3.9 (0.6)	3.8 (0.7)	−0.1 (0.2)	0.095	0.881	0.895
Resting Brachial ESS (dynes/cm^2)	31.7 (6.2)	30.0 (6.9)	−1.7 (5.4)	31.6 (6.4)	28.1 (5.1)	−3.5 (4.5)	0.398	0.674	0.022
Brachial FMD (mm)	0.30 (0.14)	0.42 (0.17)	0.12 (0.07)	0.30 (0.1)	0.25 (0.11)	−0.05 (0.08)	<0.001	0.338	<0.001
Brachial FMD (%)	8.5 (4.8)	11.5 (5.4)	3.0 (2.3)	8.2 (3.4)	7.0 (3.6)	−1.2 (1.9)	<0.001	0.191	0.061
Popliteal Diameter (mm)	5.5 (1.1)	5.8 (1.1)	0.2 (0.2)	6.6 (1.0)	6.5 (0.9)	−0.1 (0.3)	0.015	0.108	0.411
Resting Popliteal ESS (dynes/cm^2)	19.3 (3.0)	20.5 (3.0)	1.1 (2.6)	22.2 (6.6)	21.6 (4.6)	−0.6 (4.5)	0.354	0.336	0.760
Popliteal FMD (Δ mm)	0.46 (0.16)	0.62 (0.18)	0.16 (0.09)	0.53 (0.32)	0.45 (0.28)	−0.08 (0.12)	<0.001	0.349	<0.001
Popliteal FMD (%)	8.4 (2.6)	11.0 (3.3)	2.6 (1.6)	8.2 (5.0)	7.0 (4.2)	−1.2 (2.0)	0.001	0.265	0.12
Carotid Diameter (mm)	6.7 (0.6)	7.0 (0.6)	0.3 (0.2)	7.2 (0.5)	7.0 (0.6)	−0.2 (0.3)	0.001	0.348	0.301
Resting Carotid ESS (dynes/cm^2)	32.4 (5.3)	34.4 (5.9)	2.0 (5.1)	33.3 (7.5)	32.6 (6.6)	−0.7 (5.5)	0.228	0.836	0.572
VOP Forearm Basal (ml/min/100 mL tissue)	2.6 (0.8)	3.3 (1.0)	0.7 (0.7)	3.3 (0.9)	3.2 (1.1)	−0.1 (0.4)	0.003	0.469	0.019
VOP Forearm Peak (ml/min/100 mL tissue)	17.1 (4.5)	20.9 (5.7)	3.8 (2.6)	14.9 (3.9)	14.8 (3.9)	−0.1 (1.3)	<0.001	0.037	<0.001
VOP Calf Basal (ml/min/100 mL tissue)	2.7 (0.5)	3.0 (0.5)	0.3 (0.6)	3.2 (0.6)	3.2 (0.6)	0.0 (0.5)	0.134	0.143	0.126
VOP Calf Peak (ml/min/100 mL tissue)	17.6 (4.3)	22.1 (6.2)	4.5 (4.6)	17.4 (6.9)	17.4 (6.2)	0(1.2)	0.005	0.305	0.005

Data expressed as mean (SD). ESS: endothelial shear stress; FMD: flow mediated dilation; VOP: venous occlusion plethysmography.

There were significant group-by-time interactions for basal forearm blood flow (F(1,21) = 10.88, p = 0.003), peak forearm blood flow (F(1,21) = 20.17, p < 0.001), and peak calf blood flow (F(1,21) = 9.71, p = 0.005). No differences were observed in basal forearm blood flow (F(1,21) = 3.70, p = 0.068), peak forearm blood flow (F(1,21) = 1.53, p = 0.230), and peak calf blood flow (F(1,21) = 0.01, p = 0.912), while differences were found in basal calf blood flow (F(1,21) = 4.58, p = 0.044) between groups at baseline. Six weeks of boxing training led to a large increase in basal forearm blood flow (F(1,21) = 17.79, p < 0.001, η_p^2 = 0.459), peak forearm blood flow (F(1,21) = 39.94, p < 0.001, η_p^2 = 0.655), and peak calf blood flow (F(1,21) = 20.58, p < 0.001, η_p^2 = 0.495) (Figure 4 and Table 3).

https://doi.org/10.3390/sports14010005

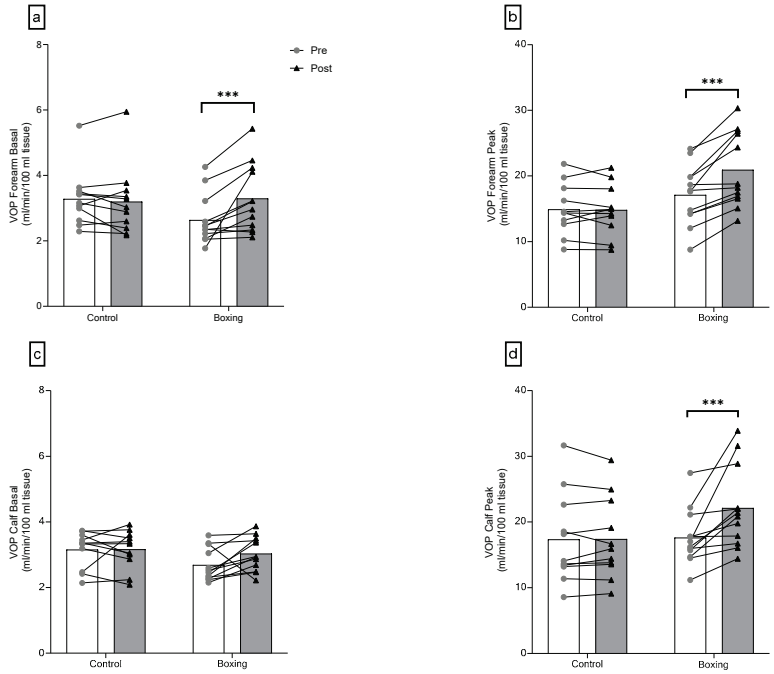


Figure 4. Plethysmography changes of the forearm (**a**,**b**) and the calf (**c**,**d**) following 6 weeks of boxing training in individuals with elevated blood pressure or stage 1 hypertension. VOP: venous occlusion plethysmography. *** $p < 0.001$.

3.5. Nitric Oxide Bioavailability

A significant group-by-time interaction was observed for NOx (F(1,20) = 10.08, $p = 0.005$). NOx was similar between groups at baseline (F(1,20) = 0.67, $p = 0.424$). A significant increase in NOx (F(1,20) = 8.37, $p = 0.009$, $\eta_p^2 = 0.295$) was found in the boxing group at the end of the intervention (Table 4).

Table 4. Blood biomarker changes following 6 weeks of intervention.

	Boxing Training			Control			Interaction	Group	Time
	Before	**After**	**Δ**	**Before**	**After**	**Δ**	***p***	***p***	***p***
NOx (μmol/L)	53.9 (19.6)	68.4 (23.3)	14.5 (17.4)	60.7 (19.9)	52.7 (26.5)	−8.0 (27.0)	0.005	0.627	0.370
CRP (mg/L)	9.1 (7.3)	5.9 (5.1)	−3.2 (3.5)	6.3 (4.4)	6.6 (4.6)	0.3 (2.3)	0.010	0.643	0.028
IL-6 (pg/mL)	19.1 (18.3)	19.0 (15.3)	−0.1 (5.7)	15.3 (13.8)	14.7 (14.9)	−0.6 (7.0)	0.851	0.546	0.810
TNFα (pg/mL)	126.9 (185.7)	134.1 (183.6)	7.2 (14.5)	91.4 (138.5)	91.1 (139.7)	−0.3 (9.0)	0.203	0.605	0.244
8-isoprostane (pg/mL)	465.1 (108.0)	487.3 (139.7)	22.2 (90.1)	440.2 (142.2)	535.7 (159.2)	95.5 (245.8)	0.364	0.792	0.152
SOD (mU/mL)	44.5 (6.2)	44.7 (6.4)	0.3 (2.2)	43.7 (6.5)	43.5 (6.9)	−0.3 (4.7)	0.731	0.710	1.000
TAC (mM/mL)	5.6 (2.5)	6.8 (3.5)	1.2 (2.4)	5.2 (2.7)	4.8 (2.0)	−0.3 (2.6)	0.151	0.242	0.408

Data expressed as mean (SD). NOx: nitric oxide; CRP: C-reactive protein; IL: interleukin; SOD: superoxide dismutase; TAC: total antioxidant capacity.

https://doi.org/10.3390/sports14010005

3.6. Inflammation

A significant group-by-time interaction was observed for CRP ($F(1,20) = 8.03$, $p = 0.01$). No differences were observed in CRP ($F(1,20) = 0.11$, $p = 0.745$), IL-6 ($F(1,20) = 0.30$, $p = 0.593$), and TNF-α ($F(1,18) = 0.23$, $p = 0.641$) between groups at baseline. Six weeks of boxing training largely reduced CRP ($F(1,20) = 13.53$, $p = 0.001$, $\eta_p^2 = 0.404$). There were no significant group-by-time interactions for IL-6 ($F(1,20) = 0.36$, $p = 0.851$) and TNF-α ($F(1,20) = 1.74$, $p = 0.203$) (Table 4).

3.7. Oxidative Stress

There were no group-by-time interactions for 8-isoprostane ($F(1,20) = 0.86$, $p = 0.364$), SOD ($F(1,20) = 0.12$, $p = 0.731$), and TAC ($F(1,20) = 2.23$, $p = 0.151$). No differences were observed in 8-isoprostane ($F(1,20) = 0.21$, $p = 0.649$), SOD ($F(1,20) = 0.07$, $p = 0.791$), and TAC ($F(1,20) = 0.16$, $p = 0.693$) between groups at baseline (Table 4).

To examine whether sex or adiposity could influence the observed intervention effects, correlation analyses were conducted between sex, baseline BMI, ΔBMI, and primary outcomes (SBP Delta, DBP Delta, ΔB_FMD%, ΔP_FMD%, ΔNOx, and ΔCRP). The complete results are presented in Supplementary Table S1. Across all predictors, correlations were weak and did not reach statistical significance. Baseline BMI and ΔBMI showed small and non-significant associations with blood pressure, vascular function, and biochemical markers. Similarly, sex demonstrated only minor correlations with changes in FMD%, NOx, and blood pressure. These findings indicate that neither sex nor adiposity meaningfully influenced the primary outcomes and support the robustness of the intervention effects after adjusting for these covariates.

4. Discussion

The present study is the first randomized controlled trial to evaluate the effects of boxing training on brachial blood pressure, central blood pressure, arterial stiffness, vascular adaptations, nitric oxide bioavailability, inflammation, and oxidative stress in individuals with elevated blood pressure or stage 1 hypertension. The primary findings we discovered indicate that 6 weeks of boxing training among this population lead to improvements in (1) clinical outcomes, including peripheral and central blood pressure, and (2) vascular outcomes, specifically enhancing conduit artery endothelial function, resistance vessel structure and endothelial function, as well as carotid artery structure. These changes are associated with an increase in NO bioavailability and a decrease in inflammation.

4.1. Peripheral and Central Blood Pressure

The present study demonstrated that 6 weeks of boxing training induced a significant reduction in brachial SBP (~16 mmHg) and DBP (~10 mmHg) in individuals with elevated blood pressure or stage 1 hypertension. Similarly, Cheema et al. [12] reported 14 and 7 mmHg reductions in SBP and DBP, respectively, after 16 weeks of boxing training in adults with abdominal obesity. The findings of the present study are also in agreement with previous meta-analyses studying the effects of exercise on blood pressure. For example, Cornelissen et al. [10] reported an overall reduction in SBP/DBP of 3.5/2.5, 1.8/3.2, and 10.9/6.2 mmHg in endurance, resistance, and isometric training, respectively, in healthy individuals or those with high blood pressure. In addition, de Sousa et al. [41] reported 8.3 and 4.1 mmHg reductions in SBP and DBP, respectively, after resistance training in individuals with high blood pressure.

Furthermore, Inder et al. [42] reported 5.2 and 3.9 mmHg reductions in SBP and DBP, respectively, after isometric exercise training in healthy individuals or with high blood

https://doi.org/10.3390/sports14010005

pressure. Moreover, Williamson et al. [43] reported 4.4 and 4.2 mmHg reductions in SBP and DBP, respectively, after a physical activity intervention in young adults with elevated blood pressure, stage 1 hypertension, or stage 2 hypertension. The SBP and DBP reductions described in those meta-analyses were lower than the reductions from the present study and the Cheema et al. study. The differences may rely on the intrinsic nature of boxing training, which is a whole-body physical activity but with an upper-body emphasis, that could induce more prominent local changes in the brachial artery (e.g., higher ESS). The blood pressure reductions following boxing training may be explained, in part, by an improvement in endothelial function, NO bioavailability, and a reduction in vascular inflammation and peripheral vascular resistance.

Lewington et al. [44] reported that a 10 mmHg reduction in SBP leads to a 30% decreased risk of coronary artery disease mortality and a 40% decreased risk of stroke mortality. In the same study, they also found that even smaller reductions (approximately 2 mmHg) in SBP resulted in a 7% decreased risk of coronary artery disease mortality and a 10% decreased risk of stroke mortality. Furthermore, Verdecchia et al. [45] reported that a 2 mmHg reduction in DBP leads to a 12% decreased risk of myocardial infarction, stroke, and cardiovascular mortality. Based on these previous findings, the results of the present study hold meaningful clinical significance.

Central hemodynamics represent the pressure in the ascending aorta and downstream (e.g., end organs). An elevation of the central blood pressure harms the vasculature and end organs, especially in the high blood pressure population [46]. Additionally, central blood pressure is recognized as a more powerful marker of end-organ damage and cardiovascular mortality compared to brachial blood pressure [47,48].

In the present study, 6 weeks of boxing training largely reduced cSBP (~8 mmHg) in individuals with elevated blood pressure or stage 1 hypertension. Similar to the findings from the present study, Beck et al. [49] reported a reduction in cSBP after 8 weeks of endurance (~11 mmHg) or resistance training (~10 mmHg) in young individuals with elevated blood pressure or stage 1 hypertension. This finding may be explained by an exercise-induced vasodilatory effect on resistance vessels in individuals with high blood pressure that reduced the magnitude of reflected pressure waves. Additionally, in the present study, no statistical reductions were observed in AIx or AIx@75 after 6 weeks of boxing training in individuals with elevated blood pressure or stage 1 hypertension. Previous studies have reported equivocal findings regarding the effects of exercise on AIx. Cheema et al. [12] reported a reduction in AIx after 16 weeks of boxing training in adults with abdominal obesity. Donley et al. [50] reported a reduction in cSBP and AIx@75 after 8 weeks of endurance training in adults with metabolic syndrome. Krustrup et al. [51] reported reductions in AIx after 12 and 24 weeks of soccer training in males with high blood pressure. Nualnim et al. [52] reported no significant reduction in AIx after 12 weeks of swimming training in elderly individuals with high blood pressure. Seals et al. [53] reported no changes in AIx after 12 weeks of walking training in older women with high blood pressure. Westhoff et al. [54] reported no changes in AIx and AIx@75 after upper-body endurance training in elderly individuals with high blood pressure. Lastly, Heffernan et al. [55] reported no changes in AIx following 12 weeks of resistance training in elderly individuals with high blood pressure. These incongruent results may be explained by the heterogeneity in exercise programs and sample characteristics (e.g., age, sex, morbidity) among studies.

Based on the findings of Vlachopoulos et al. [56], who reported that a 10 mmHg reduction in cSBP translates into an 8.8% decrease in the risk for future cardiovascular events, we propose that the findings of the present study are clinically relevant because a

https://doi.org/10.3390/sports14010005

mean reduction of ~8 mmHg was observed after 6 weeks of boxing training in individuals with elevated blood pressure or stage 1 hypertension.

Finally, in the present study, no significant reduction in LVE_W (~37%) was observed after 6 weeks of boxing in individuals with elevated blood pressure or stage 1 hypertension. LVE_W is a relatively new biomarker that describes the additional energy required by the myocardium to overcome the augmented pressure generated by the reflected pressure wave. Thus, reductions in LVE_W may prevent the progression to pathological ventricular hypertrophy secondary to high blood pressure [57]. There are only a few studies that have explored the effects of exercise on LVE_W. For example, Beck et al. [49] reported a reduction in LVEw after 8 weeks of endurance (~76%) or resistance training (~82%) in young individuals with elevated blood pressure or stage 1 hypertension. Based on these and the current study results, significant reductions in LVEw might be seen after more extended training periods.

4.2. Arterial Stiffness

Large-artery stiffness is an independent risk factor for cardiovascular mortality, and it is usually associated with high blood pressure [58]. In fact, it has been proposed that arterial stiffness is a mechanism behind the development or progression of high blood pressure [59,60]. PWVcf is the gold standard to assess arterial stiffness, and its reduction is associated with better cardiovascular outcomes [61,62].

In the present study, no changes in PWVcf were observed after 6 weeks of boxing training in individuals with elevated blood pressure and stage 1 hypertension. These findings agree with those of previous studies. Beck et al. [49] reported no changes in PWVcf after 8 weeks of endurance or resistance training in individuals with elevated blood pressure or stage 1 hypertension. Ferrier et al. [63] reported no PWVcf change following 8 weeks of cycling training in individuals with high blood pressure. Seals et al. [53] reported no effects on PWVcf after 12 weeks of endurance training in postmenopausal women with high blood. Stewart et al. [64] reported no significant changes in PWVcf after 24 weeks of endurance and resistance training in elderly individuals with high blood pressure in comparison to a control group. Lastly, Guimaraes et al. [65] reported a small reduction and no changes in PWVcf after 16 weeks of interval or continuous endurance training in individuals with high blood pressure.

In contrast, Madden et al. [66] reported ~3 m/s and ~1 m/s reductions in PWVcf after 12 and 24 weeks of endurance training in individuals with high blood pressure with other cardiovascular comorbidities. Interestingly, Collier et al. [67] reported that 4 weeks of resistance training increased PWVcf and 4 weeks of endurance training reduced PWVcf in individuals with high blood pressure. In a recent study, Bhuva et al. [68] reported a reduction in PWV across the length of the whole aorta measured by cardiovascular magnetic resonance after 24 weeks of endurance training in healthy sedentary individuals. Overall, exercise training programs shorter than 6 weeks are less likely to induce structural adaptations in elastic arteries in individuals with high blood pressure.

4.3. Vascular Adaptations

Exercise-induced vascular adaptations have been extensively reported in healthy and CVD individuals, including those suffering from high blood pressure [11,69]. These adaptations are vessel-specific (e.g., elastic, conduit, and resistance arteries) [11] and are activity-dependent (e.g., upper body versus lower body exercise) [70,71].

The present study demonstrated that 6 weeks of boxing training improves conduit artery endothelial function in individuals with elevated blood pressure or stage 1 hy-

https://doi.org/10.3390/sports14010005

pertension. Specifically, brachial and popliteal mean FMD% increased by 3% and 2.6%, respectively. These findings were in agreement with the findings of Tinken et al. [72], who reported that brachial and popliteal FMD% increased by 1.7% and 1.6% in normotensive individuals after 6 weeks of endurance training. Similarly, Beck et al. [73] showed an increase in brachial FMD% after 8 weeks of endurance training (~3.7%) and after 8 weeks of resistance training (~2.1%) in individuals with elevated blood pressure or stage 1 hypertension. In the same study, Beck et al. described a blunted endothelial response to hyperemia in individuals with elevated blood pressure or stage 1 hypertension compared to normotensive matched controls before the exercise intervention. The findings of the present study were also in agreement with previous studies involving individuals with high blood pressure. For example, Westhoff et al. [54] showed a 2.3% increase in brachial FMD% after 12-week endurance training in elderly hypertensive individuals. Swift et al. [74] reported an increase in brachial FMD% ranging from 1% to 1.5% after 24 weeks of endurance training in postmenopausal women with hypertension. Nualnim et al. [52] reported a ~3.9% increase in brachial FMD% after 12 weeks of swimming training in adults > 50 years old with high blood pressure. Finally, Molmen-Hansen et al. [75] reported a 4.2% increase in brachial FMD% after 12 weeks of HIIT in individuals with high blood pressure. These FMD% improvements might be explained by an increase in ESS during exercise, which in turn increases NO and decreases inflammation [11,76–78]. Contrary to the present findings, no changes in brachial FMD% were reported by Westhoff et al. [79] in individuals with high blood pressure after 12 weeks of upper-body endurance exercise. Differences in endothelial responses in the present study and those of Westhoff et al. may be explained by a lower ESS stimulus produced during arm-cranking in comparison to whole-body exercise. For its part, Spence et al. [80] reported a significant improvement in brachial FMD% after 24 weeks of resistance training (~1.9%) but not after 24 weeks of endurance training in young healthy individuals, while no changes were observed in femoral FMD% with either training modality.

In addition, the present study showed equivocal effects on the structure of conduit arteries after 6 weeks of boxing training in individuals with elevated blood pressure or stage 1 hypertension. Specifically, there were significant increases in resting artery diameter in the common carotid artery (~0.3 mm) and in the popliteal artery (~0.2 mm) at the end of the intervention, but not in the brachial artery. Similar findings have been described in previous studies. Dinenno et al. [81] reported an increase in diameter in the femoral artery (~0.8 mm) but not in the brachial artery after ~14 weeks of walking or jogging training in normotensive sedentary individuals. Spence et al. [80] reported an increase in diameter in the brachial artery (~0.3 mm) with resistance training but no change with endurance training, an increase in diameter in the femoral artery diameter (~0.2 mm) with endurance training but not with resistance training, and no change in diameter in the carotid artery following either exercise training modality in young healthy individuals. In contrast, no exercise-induced structural adaptations have been described in previous studies that involved individuals with high blood pressure. For example, Nualnim et al. [52] reported no changes in brachial and carotid artery diameters after 12 weeks of swimming training in adults > 50 years old with high blood pressure. Beck et al. [73] reported no change in brachial artery diameter after 8 weeks of endurance or resistance training in individuals with elevated blood pressure or stage 1 hypertension. Finally, the findings of the present study were not entirely consistent with those of Tinken et al. [72], who reported no changes in brachial and popliteal diameters in normotensive individuals throughout 8 weeks of endurance training. However, Tinken et al. described a progressive increment in vasodilator capacity in both brachial and popliteal arteries starting from week 2 in the

https://doi.org/10.3390/sports14010005

same study, which can be interpreted as an expression of artery remodeling. It has been suggested that adaptations of conduit arteries to exercise training begin with an increase in endothelial function during the first weeks, followed by artery remodeling (e.g., increase in diameter) to normalize resting ESS [11,72]. The results from the present study support this last theory, considering that resting ESS was not affected in the carotid and popliteal arteries after the boxing intervention despite the increase in diameters in both arteries.

Further, resistance vessel adaptations were also observed in the present study through venous occlusion plethysmography. The present boxing protocol increased baseline forearm blood flow (~27%), peak forearm blood flow (~22%), and peak calf blood flow (~26%). These changes reflected an augmented vascular ceiling capacity due to capillary or arteriolar proliferation and an improvement in endothelial function. These findings were in agreement with previous studies. Higashi et al. [82] reported an increase in peak forearm blood flow (~23%) in individuals with high blood pressure after 12 weeks of brisk walking. However, baseline forearm blood flow remained unchanged after the intervention. Beck et al. [32] reported an increase in baseline forearm blood flow (~22%), peak forearm flow (~31%), baseline calf blood flow (~33%), and peak calf blood flow (~44%) after 8 weeks of endurance or resistance training. Additionally, Beck et al. described that the endothelial function of resistance vessels was impaired in individuals with elevated blood pressure or stage 1 hypertension compared to normotensive controls. Based on previous studies, the findings from the present study could be explained by a reduction in sympathetic tone, metabolic changes (e.g., Angiotensin II and Endothelin-1 downregulation), and an increase in ESS [11].

4.4. Nitric Oxide Bioavailability

NO is a key molecule in the maintenance of vascular homeostasis and vascular health. NO is produced by eNOS from its substrate, L-arginine, in endothelial cells. One of the most important functions of NO is to act as a vasodilator by relaxing smooth muscle cells from the tunica media of an artery. Also, NO can inhibit platelet adhesion and aggregation, decrease ROS formation, and reduce inflammation. All these functions prevent endothelial dysfunction, which is the first step in the development of CVD [83].

As the NO half-life is relatively short, its direct quantification in blood is difficult. Estimations of NO production are best accomplished by quantification of the final NO metabolites nitrite/nitrate (NOx) [84]. The present study demonstrated that 6 weeks of boxing training in individuals with elevated blood pressure or stage 1 hypertension elevates NOx in plasma by nearly 27%. These results were in agreement with the findings of Beck et al. [73], who reported an increase in NOx after 8 weeks of cycling (~31%) and resistance training (~19%) in young individuals with elevated blood pressure or stage 1 hypertension. Similarly, Tomeleri et al. [84] reported an increase in NOx after 12 weeks of resistance training (~35%) in older women with high blood pressure, while Izadi et al. [40] reported an increment in NOx after 6 weeks of HIIT (~140%) in elderly individuals with high blood pressure. Additionally, Hasegawa et al. [85] reported an increase in NOx after 6 weeks of HIIT (~31%) and after 8 weeks of moderate-intensity cycling (~43%) in healthy young men. Moreover, Maeda et al. [86] reported an increase in NOx (~60%) following 12 weeks of cycling at 80% of the ventilatory threshold in healthy older women.

The potential mechanisms by which exercise might increase NO bioavailability in plasma are not yet fully understood. However, it is believed that vascular homeostasis is closely regulated by the mechanical interaction between blood flow and the endothelium through a process known as ESS [87]. During exercise, there is a rise in pulsatility and ESS inside arteries [11,88], which suggests that these hemodynamic changes may regu-

https://doi.org/10.3390/sports14010005

late the expression of genes involved in NO production through a mechanotransduction pathway [11,89–92].

4.5. Inflammation

Low-grade chronic inflammation has been described as a hallmark in the physiopathology of high blood pressure [93–95]. TNF-α, IL-6, and CRP are classic inflammatory biomarkers employed to explore the inflammatory state of an individual [96–98]. Several studies have shown a direct correlation between these biomarkers and high blood pressure [98–101]. TNF-α is a primary inflammatory cytokine released by white blood cells that stimulates visceral adipose tissue to secrete IL-6, a secondary inflammatory cytokine, which in turn increases the production and excretion of CRP from the hepatocyte [100,102,103]. Additionally, CRP can be secreted by other cell types, including endothelial cells [104], where it has been shown to have deleterious autocrine and paracrine effects on them (e.g., overexpression of adhesion molecules) [105–107]. In the present study, CRP decreases after 6 weeks of boxing training, but neither TNF-α nor IL-6 does. These findings can be explained by the fact that a short period of exercise training (e.g., 6 weeks) by itself does not significantly affect body fat mass and specifically the amount of adipose tissue; consequently, there may be no significant modification in the adipocyte signaling pathway to alter TNF-α and IL-6 production. Conversely, CRP reductions could be the result of an exercise-induced signal (e.g., mechanotransduction or myokines) that directly enhances endothelial function and inhibits CRP secretion into the bloodstream. A reduction in CRP may indicate a direct downregulation of vascular inflammation, which in turn helps prevent high blood pressure.

The results of the present study were in agreement with those of Lamina et al. [108], who reported a CRP reduction after 8 weeks of cycling training at moderate intensity in individuals with high blood pressure. Interestingly, baseline CRP levels differed between studies. While Lamina et al.'s study reported a baseline mean CRP value below 1 mg/L, which is considered to be in the non-inflammatory range, the present study showed a baseline mean CRP value above 3 mg/L, which is categorized as high risk for the development of cardiovascular events [107,109]. These results confirm that exercise can be employed as an anti-inflammatory strategy for individuals with high blood pressure.

4.6. Oxidative Stress

Oxidative stress is another feature associated with the pathophysiology of high blood pressure [4,95,110]. In the present study, no changes were observed in oxidative stress status as observed by the measurements of 8-isoprostane, SOD, and TAC in the plasma of individuals with elevated blood pressure or stage 1 hypertension after 6 weeks of boxing training. These findings were incongruent with previous studies. Feairheller et al. [111] reported an increase in plasma TAC (~9%) and urinary 8-isoprostane (~31%) after 24 weeks of endurance training at 70% VO_2max in individuals with high blood pressure. Beck et al. [32] reported a reduction in plasma 8-isoprostane (~43%) and an increase in plasma TAC (~43%) after 8 weeks of resistance training and a reduction in plasma 8-isoprostane (~40%) and an increase in plasma TAC (~42%) after 8 weeks of endurance training in individuals with elevated blood pressure and stage 1 hypertension. Lastly, Dantas et al. [112] reported an increase in plasma TAC (~12%) after 12 weeks of resistance training in older women with high blood pressure. Differences in the oxidative stress responses between the present study and previous studies may be explained by the length of each exercise program. The present study involved only 6 weeks of training, while the other studies lasted from 8 to 24 weeks.

https://doi.org/10.3390/sports14010005

Additional analyses were performed to evaluate whether sex or adiposity may have confounded the intervention outcomes. The correlations between sex, baseline BMI, ΔBMI, and all primary variables were consistently weak and non-significant (Supplementary Table S1). These results suggest that the improvements observed in blood pressure, endothelial function, and biochemical markers were not attributable to differences in adiposity or sex. Although exercise training can promote weight loss that may contribute to blood pressure reductions, the ΔBMI values in the present study were modest and did not correlate significantly with changes in SBP, DBP, or vascular outcomes. Taken together, the data reinforce that the beneficial effects of the intervention are more likely due to the physiological stimulus of training rather than changes in body weight or demographic differences.

The major strengths of this study include its randomized controlled design, the use of objective and gold-standard vascular measures (FMD, PWA, PWV, and VOP), and highly adherent training in the intervention group. However, the present study was not without limitations. First, only young adults (<35 years old) participated in this study, which may limit the generalization of the present results to only young individuals with elevated blood pressure or stage 1 hypertension. Second, a dietary record was not employed to ensure that a low-nitrate diet was followed prior to blood collection, which could have affected the results of some biomarkers. Third, structural adaptations in muscular arteries may be better represented by the conduit dilator capacity rather than the artery diameter, which was not measured in the present study. Lastly, a key limitation of this study is the disparity in adherence between the Boxing (98.1%) and Control (27.3%) groups. The significantly lower adherence in the Control group, potentially due to the inherent lack of engagement in a non-exercise, stretching/balance protocol, may introduce bias. Furthermore, the difference in adherence levels means there was likely an unequal effect of investigator contact and supervision between groups, which could have partially accounted for the observed changes in the intervention group. We acknowledge this as a limitation; however, the magnitude of the cardiovascular and vascular improvements observed strongly suggests that the physiological effects of the high-intensity boxing training were the primary drivers of the positive outcomes. It is important to note that the methodology used for cardiovascular risk stratification in this study precedes the release of the updated 2025 AHA/ACC BP guidelines, which now recommend utilizing the PREVENT risk calculator instead of the Pooled Cohort Equations for risk assessment. Future boxing training studies in individuals with elevated blood pressure or stage 1 hypertension should include an elderly population or be part of a community-based program to determine if the results of the present study can be generalized.

5. Conclusions

In conclusion, the present study demonstrated that a 6-week, 3 days per week boxing training program successfully reduced SBP, DBP, and cSBP while improving vascular health in individuals with elevated blood pressure or stage 1 hypertension. These effects may be explained, in part, by a reversal of some pathological pathways involved with high blood pressure, such as endothelial dysfunction, NO bioavailability, peripheral vascular resistance, and inflammation. Further, boxing training could be recommended as an exercise alternative in the management of the early stages of high blood pressure.

https://doi.org/10.3390/sports14010005

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/sports14010005/s1, Table S1: Correlations between sex, baseline BMI, ΔBMI, and primary vascular outcomes.

Author Contributions: F.M.-A. and A.N.G. conceived and designed research; F.M.-A., M.G., L.R. and P.C. performed experiments; F.M.-A. analyzed data; F.M.-A. and A.N.G. interpreted results of experiments; F.M.-A. and M.M.-Á. prepared figures; F.M.-A. drafted manuscript; A.N.G. and M.M.-Á. edited and revised manuscript. All authors approved final version of manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: The Dodson Research Grant of The University of Texas at El Paso supported this study.

Institutional Review Board Statement: This study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board of The University of Texas at El Paso (UTEP IRB Study Number 1364179-3, approval date: 22 February 2019).

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

Data Availability Statement: The datasets employed in this study can be obtained from the corresponding author upon reasonable request. However, certain data cannot be made publicly accessible due to privacy considerations.

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

Abbreviations

The following abbreviations are used in this manuscript:

ACC/AHA	American College of Cardiology/American Heart Association
AIx	Augmentation index
AIx@75	Augmentation index normalized to a heart rate of 75 bpm
ANOVA	Analysis of variance
CBF	Calf blood flow
cSBP	Central systolic blood pressure
cDBP	Central diastolic blood pressure
cPP	Central pulse pressure
cAIx	Central augmentation index
CVD	Cardiovascular diseases
D	Diameter
DBP	Diastolic blood pressure
ESS	Endothelial shear stress
FBF	Forearm blood flow
FMD	Flow-mediated dilation
LVEW	Left ventricular energy
NO	Nitric oxide
NOx	Nitric oxide metabolites nitrite/nitrate
PP	Pulse pressure
PWA	Pulse wave analysis
PWVcf	Pulse wave velocity carotid–femoral
RPE	Rate of perceived exertion
SBP	Systolic blood pressure
SD	Standard deviation
VOP	Venous occlusion plethysmography

https://doi.org/10.3390/sports14010005

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https://doi.org/10.3390/sports14010005

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Article

Association of Controlled Physical Activity with Weight Loss and Less Limitations for Hypertensive Patients

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Abstract: Background: The overweight population is a major public health problem which is typical for the 21st century, considering the peak of the noncommunicable diseases (NCDs). The connection between hypertension—the number-one risk factor of cardiovascular diseases (CVDs)—and the body mass index (BMI), which is growing worldwide, needs to be taken into consideration. Methods: Four homogeneous groups of twenty-five patients each with hypertension degree 1 benefited from different 8-week recovery programs: recommendation for a healthy lifestyle (all groups—A, B, C and D), antihypertensive medication (groups B, C and D), physical therapy program (group C), and hydrotherapy program (group D). Four parameters were pursued: body mass index (BMI), waist circumference (Wcir.), and systolic and diastolic blood pressure (SBP-DBP). Results: Intragroup comparison between initial and final testing registered a statistically significant decrease in all parameters for group C: BMI ($p = 0.001$), Wcir, SBP and DBP ($p < 0.0001$). Additionally, parameters of group D decreased significantly: BMI ($p = 0.0005$), Wcir, SBP and DBP (each $p < 0.0001$). Group A registered a statistical increase in the DPB parameter ($p = 0.03$), and group B had a significant decrease in SBP ($p = 0.03$). Conclusions: Implication in established physical therapy and hydrotherapy had a better outcome in diminishing all four parameters compared to the recommendations for a healthy lifestyle when patients had to improve their lifestyle by themselves, unsupervised.

Keywords: hypertension; BMI; waist circumference; exercises; hydrotherapy

1. Introduction

In the last 10 years, medical science has placed hypertension on the top of the list of cardiovascular risks, with hyperlipidemia and diabetes second and third, which are linked, in most cases, to nutritional habits; the fourth and fifth are obesity and bad diets, and then the last is smoking [1–3]. Not more than five years ago, statistics showed that

Europe had 30 million patients with CVDs, and the estimated number of new cases for each year passing is 13 million [4].

Almost 30 years ago, cardiovascular diseases were described as an epidemic for developing countries, and today they are presented as a global burden. Because CVDs were named a silent pandemic, the interventions become imminent. Even with all precautions, the number of hypertensive patients is constantly increasing, and it appears to be nearly impossible to stop; by 2015, it reached 1.13 billion globally [5–7]. In the 2021 ESC guide, there is no topic focused on hypertension, but we do observe it mentioned in the top risk factors for arterial fibrillation, along with obesity, both marked in red [8]. Three years later, in 2024, the newest guidelines underlined the acute need to intervene from as many directions as possible regarding the hypertensive population [9].

Millions of new cardiovascular patients are registered every year around the world, and approximately 50% of them have hypertension as diagnosis. Today, obesity is more often associated with cardiovascular diseases. BMI has been the first concern among the risk factors in cardiovascular diseases, especially because in some countries, in 2021, 54% of the adult population was overweight or obese. From the perspective of new CVD cases, in 2021, a majority of patients were from urban areas, and also, regarding gender, most of the patients were women, but in rural areas and among men, mortality was more prevalent [10–12].

It is alarming that, in the last decade, groundwork showed the connection between modified BMI and high blood pressure even among children and young adults [13,14]. The data show an annual growth rate for obesity between 0.2% and 7.7%, predominant in most countries [15]. The estimated data for the next five years indicate continuously raising values for blood pressure and BMI. Nowadays, the number-one concern is to reduce the mortality rate of NCDs (noncommunicable diseases) in general and specifically in CVDs (cardiovascular diseases) in order to stop the predicted sequence for 2030 [16–18] with simple and effective measures which will be easily accepted by populational groups at risk.

Current studies that investigated the effects on physical activities have shown conflicting results of hypertensive patients. A study based on recommendations for physical activity showed no impact from reducing blood pressure values on hypertensive patients [19]. A high-intensity training program registered limited decreases in blood pressure values in hypertensive patients with no scientific relevance, while a study based on a functional training revealed diminished blood pressure values after the program [20,21]. Further research is needed to provide proper intervention for hypertensive patients.

Therefore, this study pursued the impact of four different interventional approaches, i.e., recommendations for a healthy lifestyle, antihypertensive medication, physical therapy program and hydrotherapy, on body mass index, waist circumference and blood pressure values for hypertensive patients.

The main purpose was to evaluate whether changes in the two anthropometric parameters and, implicitly, the applied program will influence the BP values. According to the hypothesis, the 8-week interventional programs are expected to decrease BMI and waist circumference, leading to a decrease in blood pressure values as well. Recognizing the potential importance of training and professional interventions in BMI, Wcir, DBP and SPB can help in the identification of contributing factors and the clinical interpretation of the parameters for hypertensive patients.

2. Materials and Methods

2.1. Study Design

More than 250 patients diagnosed with degree 1 hypertension were selected from the cardiologist's records of the county, at the beginning of 2023. Their personal clinical files were analyzed, informed consent was obtained and inclusion criteria were met.

Patients were eligible for the study if they met the following inclusion and exclusion criteria. Criteria that determinate inclusion: (1) age between 30 and 60 years old; (2) hypertension degree 1 with SBP 140–159 mmHg and DBP 90–99 mmHg [22,23], recently cardiology diagnosed and without previous treatments, neither pharmaceutical nor non-pharmaceutical; and (3) written consent signed for both sections ((a) analysis of the medical records; and (b) active implication in the recovery program and assessments during the study). Criteria determining exclusion: (1) pregnant or postpartum period for woman; (2) SBP or DPB values with a higher difference of 15 mmHg between arms; (3) dermatological or other skin pathology that may be contraindicated in physical therapy or hydrotherapy; (4) chronic diseases associated; (5) inflammatory diseases that may influence their physical implication in the recovery program; and (6) medication treatment that may influence the BP values—other than antihypertensive drug treatment recently prescribed, only if required.

The patients meeting the inclusion and exclusion criteria were divided into 4 homogenized groups subsequent to age, and nine homogeneity criteria were fulfilled. Consequently, this prospective interventional study was conducted with 100 patients divided into four homogeneous groups, named A, B, C and D, with 25 individuals each (Table 1).

Table 1. Patient groups' baseline subsequent to homogenized criteria.

		A	B	C	D
		***n* (%)**	***n* (%)**	***n* (%)**	***n* (%)**
Sex					
	F	16 (64)	16 (64)	16 (64)	16 (64)
	M	9 (36)	9 (36)	9 (36)	9 (36)
Menstruating					
	Not applicable	9 (36)	9 (36)	9 (36)	9 (36)
	Yes	4 (16)	4 (16)	4 (16)	4 (16)
	No	12	12	12	12
Menopause early					
	Not applicable	9 (36)	9 (36)	9 (36)	9 (36)
	Yes	10 (40)	10 (40)	10 (40)	10 (40)
	No	6 (24)	6 (24)	6 (24)	6 (24)
Familial history of HBP					
	Yes	20 (80)	20 (80)	20 (80)	20 (80)
	No	5 (20)	5 (20)	5 (20)	5 (20)
Smoking					
	Yes	7 (28)	7 (28)	7 (28)	7 (28)
	No	18 (72)	8 (72)	8 (72)	8 (72)
Overweight					
	Yes	21 (84)	21 (84)	21 (84)	21 (84)
	No	4 (16)	4 (16)	4 (16)	4 (16)
Active lifestyle					
	Yes	6 (24)	6 (24)	6 (24)	6 (24)
	No	19 (76)	19 (76)	19 (76)	19 (76)
Active work					
	Yes	8 (32)	8 (32)	8 (32)	8 (32)
	No	17 (68)	17 (68)	17 (68)	17 (68)
Difference BP value between arms					
	Yes	4 (16)	4 (16)	4 (16)	4 (16)
	No	21 (84)	21 (84)	21 (84)	21 (84)

A, B, C and D: groups of patients. BP: blood pressure.

2.2. Intervention

Each of the four groups had a different interventional approach:

→ Group A benefited from recommendations for a healthy lifestyle.
→ Group B, besides counseling for a healthy lifestyle, started administering antihypertensive medication prescribed by the cardiologist.
→ Group C had both interventions described previously, i.e., healthy lifestyle counseling and medication, along with an interventional program based on physical therapy.
→ Group D received both the interventions that were previously described, i.e., healthy lifestyle counseling and medication, along with an interventional program based on hydrotherapy.

2.2.1. Recommendations for a Healthy Lifestyle

The counseling based on the WHO recommendation aims to improve health by explaining the behavioral risk factors for the cardiovascular system that need to be reduced or excluded if possible. All patients from groups A, B, C and D were instructed to fulfill changes in four directions: unhealthy diet, sedentarism, smoking and alcohol consumption.

Regarding diet, the number-one concern was the salt consumption, which was recommended to be diminished as much as possible. Processed food was highly recommended to be substituted with fresh vegetables, fruits, white meat and fish. Adequate water intake, in addition to avoiding juice and especially fizzy drinks, was also recommended.

Smoking needs to be reduced or excluded if possible, taking into consideration the patient's addiction, type and number of cigarettes per day in order to estimate the nicotine withdrawal timeline for these patients. We strongly recommend avoiding alcohol, especially the refined type; for optimal results, abstinence for several weeks, during the implemented program, is recommended.

Sedentarism is a constant struggle that needs to be combatted. Recommendations sought to initiate more physical activity in their free time or at work, if possible, in order to have moderate activity daily and 2–3 sessions of intense exercise weekly. If none of this is possible, due to lack of time or interest in any physical activity, walks are the most beneficial alternative, combined with gardening or cycling. An observation needs to be made regarding life nowadays: daily chores are no longer considered physical activity [24,25].

2.2.2. Antihypertensive Medication

Based on patients' anamnestic data, the cardiologist prescribed the most suitable antihypertensives for the patients of groups B, C and D. The latest studies' outcomes sustain prescription of pharmaceutical therapy for lowering blood pressure, based on the practical algorithm that sustains starting the treatment with angiotensin-converting enzyme inhibitor (ACEi) or angiotensin receptor blocker (ARB) in combination with diuretics or low-dose non-dihydropyridines calcium channel blockers [26].

2.2.3. Physical Therapy Program

Twenty sessions of physical activity coordinated by specialists in kinetic recovery were implemented for group C. There was an 8-week program conducted in group sessions of 5 to 8 patients, with a frequency of 2–3 sessions weekly. Each session was organized following kinesiotherapy criteria: preparation of the body for the effort with static stretching exercise (10–15 poses sustained for 30 s each), active part with progressive overload constituted in a varied circuits type and adequate recovery post-exercises. From the total time of a session, 50–70 min, the main active part may reach up to 45 min in order to

enhance cardiovascular endurance. This dominant section was subdivided into two parts: one represented by a circuit with varied exercise and another one compounded by cycling or walking on a treadmill, using an individualized speed and time ratio for each patient [27,28].

2.2.4. Hydrotherapy Program

Hydrothermal therapy, implemented for group D, consists of 20 sessions of 50–70 min each, with a frequency of 2 to 3 meetings weekly for 8 weeks in a row. To prepare the body for exertion, a few techniques from the physiotherapy section were chosen, i.e., electrotherapy, magnetotherapy, four cellular galvanic baths, paraffin and mud applications. The predominate active part reaches up to 45 min, and it is represented by exercise in the pool combined with walking and climbing stairs by using the resistance of water at different submersion levels. The recovery after the effort was also carried out in the pool, under the recommendations of freestyle swimming and flouting. All patients benefited from floating devises during practice in order to keep them safe and secure [29].

2.3. Evaluation

Participants who were enrolled were required to visit the laboratory twice during the prospective interventional study: first, for an initial assessment, before implementing the program; and then for a final assessment after 8 weeks of the predetermined program.

All visits were performed during the same daytime hours, in the afternoon, between 14 and 15 to avoid differences that may be induced by diurnal variation. Upon arrival at the laboratory, the anthropometrics measurements of the patients—BMI and waist circumference—were obtained by trained research assistants respecting standardized protocols. For height measurement, a moveable anthropometer was used, and patients were in an orthostatic position, with bare feet on a flat surface, with the weight equally distributed on both feet and the head in the Frankfort Horizontal Plane. A certified standard scale was used with accuracy within 50 g [30].

Monitoring and measuring blood pressure took place in the same conditions for all patients, taking into consideration the impact of the white-coat phenomenon and the training needed for both patients and specialists. Several measurements have been made to obtain the most accurate value: blood pressure measurement is made after 5 min of physical and psychological rest; three measurements in a row are made, and the value obtained from the arithmetic average of the last two is written down [31,32].

BMI formula and classification did not change over time and remain an important parameter for the health in general and for the morbidity risks: BMI = weight (kg) ÷ height^2 (meters). Interpretation BMI: underweight, <18.5 kg/m^2; healthy, 18.5–24.9 kg/m^2, overweight, 25–29.9 kg/m^2; obesity, 30–39.9 kg/m^2; and severe obesity, >40 kg/m^2 [33,34].

For waist circumference measurements, a flexible steel tape calibrated in centimeters within millimeter graduation will be placed comfortably but still tight around the lateral aspect of each ilium at the mid-axillary line, with the patients standing with their arms crossed on opposite shoulders from the orthostatic position [35].

Waist circumference has gained its place alongside BMI as an indicator that comes to underline potential cardiovascular risks. Studies suggest that BMI analysis completed with waist circumference will bring a superior view regarding obesity in general, but mostly in correlation with cardiovascular diseases. Optimal waist circumference is <94 cm for men and <80 cm for women; measurements that register a waist circumference higher than 102 cm for men and higher than 88 cm for women are corelated with a major cardiovascular risk [36].

2.4. Statistical Analysis

Statistical analysis was performed using GraphPad Prism V.9. To evaluate the data normality, the Shapiro–Wilk test was used. To make comparisons between groups' data with a normal distribution, we used Student's *t*-test for dependent data, and the Wilcoxon test when data were not normally distributed. In both cases, in order to compare the initial result with the final ones within each group, the outcomes with a $p \leq 0.05$ were considered statistically significant.

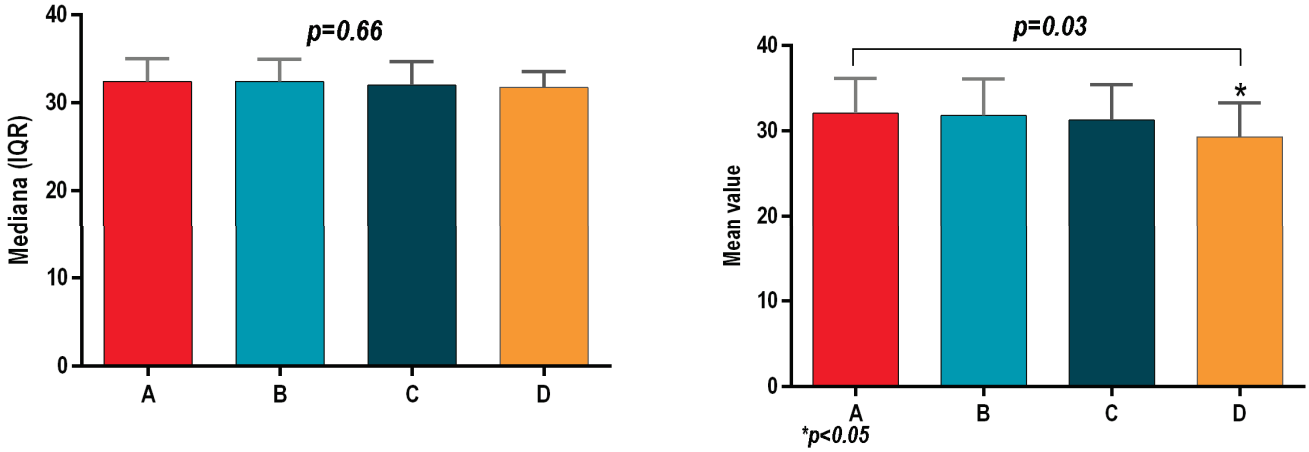
For the comparison between multiple groups, we used the ANOVA test for numeric values with normal distribution and the Kruskal–Wallis test for values not normally distributed. Also, for the post hoc analysis, we applied Tukey's multiple comparisons test and Dunn's multiple comparisons test. The results are expressed as arithmetic mean ± standard deviation and as median (IQR). The level of statistical significance was set for $p \leq 0.05$.

3. Results

3.1. Initial and Final Intergroup Testing

In regard to age, the groups had no statistical differences: group A had an age mean of 46.12 ± 7.78, group B had an age mean of 45.96 ± 7.27, group C had an age mean of 46.32 ± 7.50 and group D had an age mean of 46.08 ± 7.83. Additionally, ANOVA analysis disclosed no significant statistical difference among groups, $p = 0.99$.

All patients of groups A, B, C and D registered similar outcomes at the initial assessment, with no statistically significant differences for body mass index (BMI $p = 0.66$; Figure 1a), waist circumference (Wcir $p = 0.98$, Figure 2a), and systolic and diastolic blood pressure (SBP, $p = 0.83$; DBP, $p = 0.7$; Figures 3a and 4a). Before the interventional programs, the baseline parameters analyzed using the statistical ANOVA test showed homogeneity among all four groups for all parameters, $p > 0.05$.



(**a**) (**b**)

Figure 1. (**a**) Initial assessment of body mass index (BMI) for groups A, B, C and D. (**b**) Final assessment of body mass index (BMI) for groups A, B, C and D. $p \leq 0.5$ was considered significant.

Statistically significant differences were observed among groups in all parameters, such as body mass index, waist circumference, and systolic and diastolic blood pressure, when analyzed via the ANOVA test following 8 weeks of the implemented programs ($p < 0.05$).

Figure 1a presents the initial assessment for body mass index, which had no statistically significant intergroup differences: A (32.46 (30.44–35.01)), B (32.45 (29.02–34.97)), C (32 (30.35–34.68)) and (D 31.77 (28.9–33.55)); BMI $p = 0.66$.

Figure 1b shows the body mass index of groups A, B, C and D after 8 weeks of the final assessment, where the best outcome was registered by the hydrotherapy program of group D, with (29.33 ± 3.96), which, compared to group A (32.10 ± 4.07), showed a statistically significant decrease, $p = 0.03$. Group B (32.10 ± 4.07) registered the same values as group A. Group C's mean (31.27 ± 4.17) was lower than that of groups A and B, and it was higher than the mean of group D, but there are no statistically significant differences between any of them.

Figure 2a shows that the initial assessment for waist circumference (Wcir) had no statistically significant intergroup differences: A (89 (84.5–99.5), B (89 (85.5–101.5), C (89 (85–99.5) and D (89 (85–99.5); Wcir $p = 0.98$.

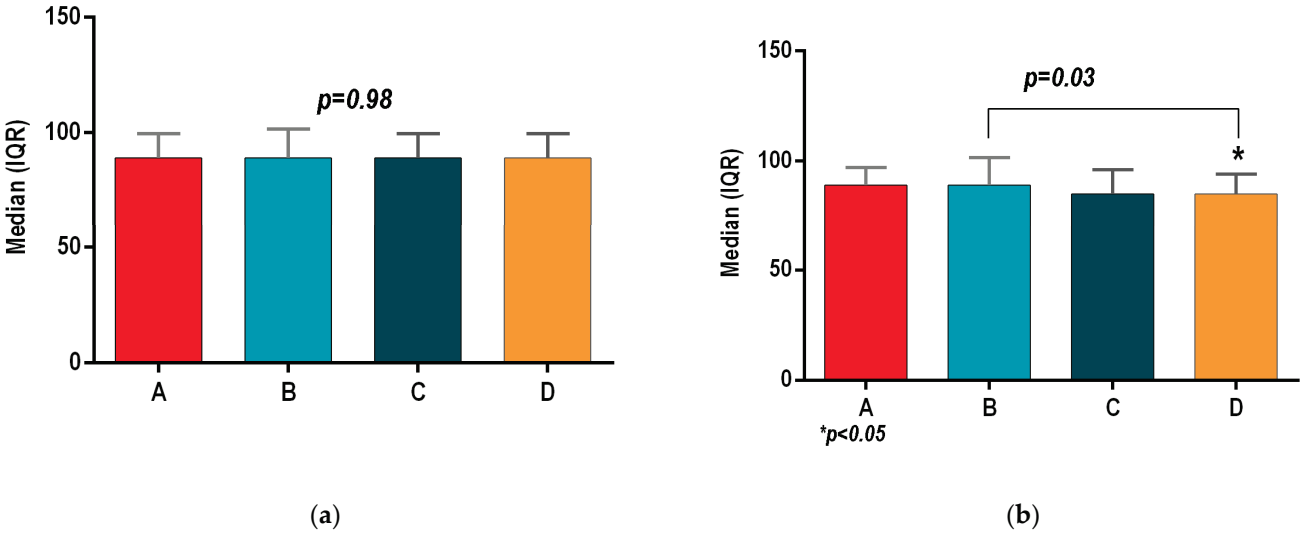


Figure 2. (**a**) Initial assessment of waist circumference for groups A, B, C and D. (**b**) Final assessment of waist circumference for groups A, B, C and D. $p \leq 0.5$ was considered significant.

After 8 weeks of final assessment, Figure 2b presents the second anthropometric parameter, waist circumferences (Wcir), of groups, B, C and D. The hydrotherapeutic program of group D, once again, was the most effective: Wcir = 85 (81–94) when compared to group B, which registered Wcir = 89 (85–101.5) with statistically significant difference $p = 0.03$. The Wcir results of group A, 89 (85–97), were similar to the group B, and the results of group C, 85 (81.5–96), were similar to the results of group D, but there were no statistically significant differences between any of them.

Figure 3a shows that the initial assessment for systolic blood pressure had no statistically significant intergroup differences: A (148 (143.5–151.5), B (150 (145–154.5), C (151 (144–155) and D (150 (144–156.5), SBP $p = 0.83$.

According to the 8-week final evaluation, systolic blood pressure revealed that the hydrotherapy program in group D (143 (140–147) and the physical therapy in group C (144 (141–148) both showed a statistically significant decrease when compared to group A (151 (143–157), SBP $p = 0{,}002$, Figure 3b. Group B's outcome registered SBP (144 (141–148) values close to those of group A, but there were no statistically significant differences between them or between group B and groups C and D.

Figure 4a shows the initial assessment for diastolic blood pressure had no statistically significant differences intergroup: A (94 (92–96), B (93 (90–95), C (94 (93–96.5) and (D94 (92–96), DBP $p = 0.7$.

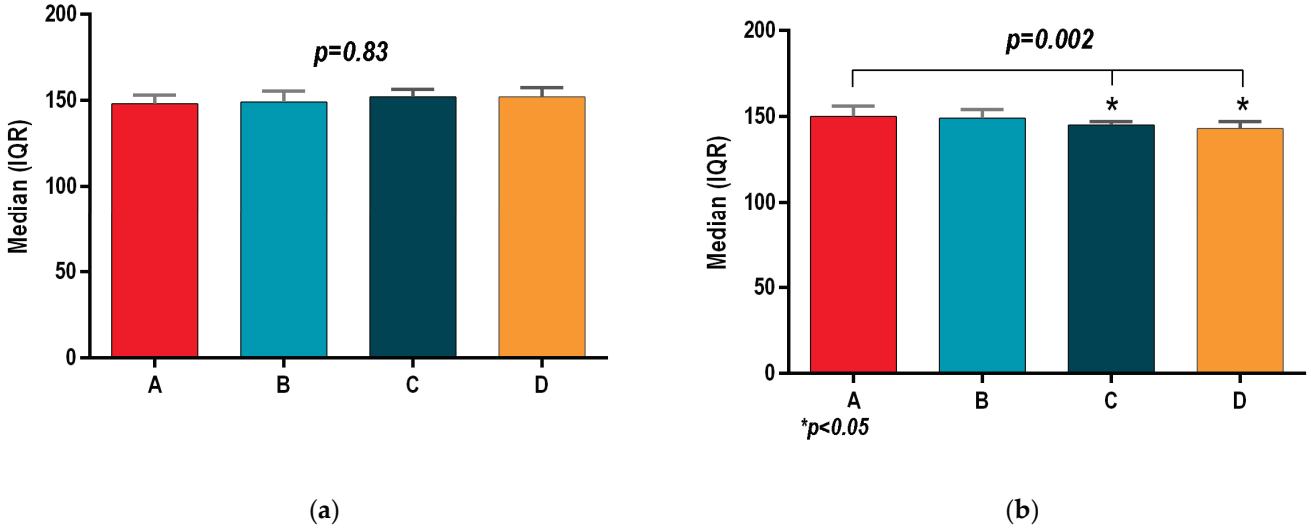


Figure 3. (**a**) Initial assessment of systolic blood pressure (SBP) for groups A, B, C and D. (**b**) Final assessment of systolic blood pressure (SBP) for groups A, B, C and D; $p \leq 0.5$ was considered significant.

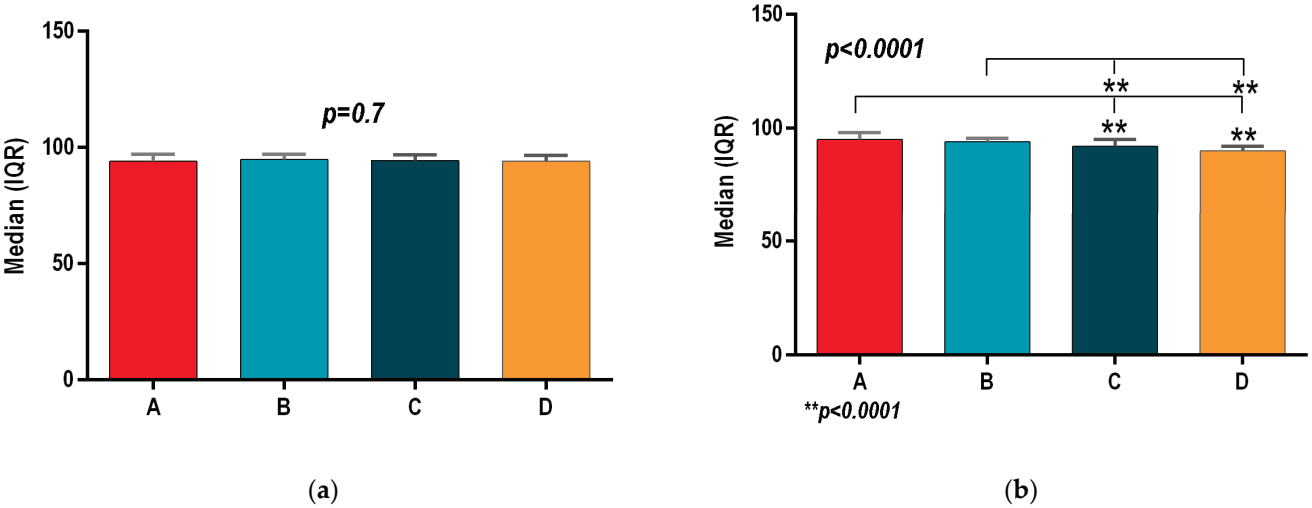


Figure 4. (**a**) Initial assessment of diastolic blood pressure (DBP) for groups A, B, C and D. (**b**) Final assessment of diastolic blood pressure (DBP) for groups A, B, C and D. $p \leq 0.5$ was considered significant.

Figure 4b reveals the 8-week outcome of diastolic blood pressure (DBP) for both interventional programs, i.e., physical therapy of group C (92 (90–94)) and hydrotherapy of group D (91 (89.5–92)), indicated a statistically significant difference in the final assessment compared to the other two groups: group A (95 (93–97.5))—benefited from recommendation for healthy lifestyle; and group B (94 (93–96.5))—received antihypertensive medication, along with recommendation for healthy lifestyle; both comparisons showed DBP $p < 0.0001$.

All in all, the hydrotherapy program combined with recommendations for a healthy lifestyle and antihypertensive medication for group D achieved the lowest means and medians for all parameters at the final assessments, when comparing with the other three groups: BMI $p = 0.03$, Wcir $p = 0.03$, SBP $p = 0.002$ and DBP $p < 0.0001$ when compared with groups A and B. The physical therapy combined with recommendations for a healthy

lifestyle and antihypertensive medication made group C's values close to group D's values: SBP $p = 0.002$ and DBP $p < 0.0001$ when compared with groups A and B. At this point, there was no statistically significant difference between hydrotherapy programs and physical therapy programs.

Furthermore, both groups A and B registered higher means and medians in two different parameters. Group A registered higher values for systolic and diastolic blood pressure, showing that the recommendation for a healthy lifestyle may have an impact on body mass index and waist circumference but not on blood pressure values. Group B recommended a healthy lifestyle in combination with antihypertensive medication that had the highest values for body mass index and waist circumference, indicating that medication has a positive impact on blood pressure values but may not bring any improvements regarding anthropometrics parameters. Nevertheless, there was no statistically significant difference between groups A and B.

3.2. Comparisons of Initial and Final Assessment in Intragroup A, B, C and D

Intragroup comparison of initial and final assessments revealed that groups A and B had a statistically significant difference for only one parameter each, while groups C and D had statistically significant differences for all of their parameters (Table 2).

Table 2. Initial and final assessment, comparison of intragroup A, B, C and D.

		Initial	Final	*p* Value
Group A				
	BMI	32.0 ± 4.18	32.10 ± 4.07	0.12
	Wcir	91.52 ± 8.92	91.6 ± 8.48	0.7989
	SBP	148.6 ± 5.30	149.9 ± 10.12	0.45
	DPB	94.16 ± 2.52	95.2 ± 2.73	0.03
Group B				
	BMI	32 ± 4.18	32.1 ± 4.07	0.12
	Wcir	91.88 ± 8.37	91.80 ± 8.49	0.8184
	SBP	149.8 ± 6.18	149 ± 5.62	0.03
	DPB	94.72 ± 2.42	94.4 ± 2.44	0.33
Group C				
	BMI	32 (30.35–34.68)	31.55 (29.64–33.97)	0.001
	Wcir	91.96 ± 8.86	88.72 ± 8.46	<0.0001
	SBP	151 (144–155)	144 (141–148)	<0.0001
	DPB	94 (93–96.5)	92 (90–94)	<0.0001
Group D				
	BMI	31.77 (28.9–33.55)	30.49 (27.89–32.16)	0.0005
	Wcir	91.56 ± 8.82	86.56 ± 7.61	<0.0001
	SBP	150 (144–156.5)	143 (140–147)	<0.0001
	DPB	94 (92–96)	91 (89.5–92)	<0.0001

BMI, body mass index; Wcir, waist circumference; SBP, systolic blood pressure; DBP, diastolic blood pressure; $p \leq 0.5$ was considered significant.

Group A registered a statistically significant increase in DBP with $p = 0.03$, and for the other three parameters, BMI, waist circumference and SBP, the group indicated non-statistically significant values. Group B, which benefited from recommendations for a healthy lifestyle and antihypertensive medication, registered decreased blood pressure values, but only the systolic blood pressure (SBP) was statistically significant, with $p = 0.03$; further, a small decrease in waist circumference meant a slight increase in BMI, but it was not statistically significant (Table 2).

Group C, which, besides receiving recommendations for a healthy lifestyle and pharmaceutical intervention, had a specialized physical recovery program, registered a decrease in all four parameters, with all being statistically significant: BMI ($p = 0.001$), Wcir, SBP and DBP (each had $p < 0.0001$). Group D, which participated in a hydrotherapy program, along with receiving recommendations for a healthy lifestyle and pharmaceutical antihypertensive treatment, achieved a statistically significant decrease in all parameters: BMI had $p = 0.0005$, and each Wcir, SBP and DBP had $p < 0.0001$ (Table 2).

The outcome of group D is to be taken into consideration given the fact that it registered better results compared to all other groups—A, B and C. The mean of BMI dropout was 1.28 points after the 8-week hydrotherapy program—group D; and with 0.73 points after the 8-week physical therapy—group C. The difference noticed for the DBP parameter was a decrease of 3 units mmHg for group D and 2 units mmHg for group C. Regarding the means of waist circumference and systolic blood pressure, both recovery programs registered the same dropout after the 8-week interventions: 4 cm for Wcir and 7 units mmHg for SBP (Table 2).

4. Discussion

The study aims to demonstrate BMI and waist circumference reduction with a therapeutic intervention consisting of directions on how to obtain a healthy lifestyle, antihypertensive medication, and specialized programs of physical therapy and hydrotherapy, along with self-control of regular blood pressure values, in an 8-week period for a group of hypertensive patients.

The results of this study show that active implication in established physical therapy or hydrotherapy had a better outcome compared with only recommendation for a healthy lifestyle when the patients needed to do all by themselves unsupervised. Regardless of the expectations, online programs of physical activity proved to be ineffective; for instance, a thermoneutral-water home program did not reach the expected results [37,38]. Therefore, recovery programs based on the direct implication of the trained specialists are most likely irreplaceable.

The recommendation for a healthy lifestyle did not bring any benefits to the patients of group A after the 8-week period; the DBP median, which was higher at the end than the beginning of the implementation of the program, indicated progression of hypertension.

B group, besides receiving the healthy lifestyle recommendations, initiated pharmaceutical treatment, and the results are statistically significant for one parameter: the SBP median was lower after the 8-week program. The cases in which lifestyle changes are related to weight loss and controlled BP values are isolated. At this point, in our study, antihypertensive medication brought additional benefits to the patients that most likely will reduce cardiovascular risks.

The association of medication with physical therapy or hydrotherapy programs had a better outcome for groups C and D in comparison with groups A and B. Both programs brought statistically significant changes for all documented parameters. Once more, it is underlined that systematic and specialized supervised programs are more likely to bring better results in comparison to a free-will program based on theoretical recommendations that the patients need to implement by themselves. Periodical assessments and theoretical recommendations may not be sufficient; a direct implementation and specialized supervision, like in the two recovery-group programs described in this study, represent a more effective path for hypertensive patients.

The current research assessed the impact of four different approaches to controlling the body mass index, waist circumference and blood pressure values of hypertensive

patients. The relation between obesity, expressed by high BMI, and hypertension has often been pointed out in studies over the last 5 years [39–41]. It is alarming that more studies take into consideration the connection mentioned above, regardless of the age population [42,43]. The interventions are yet to be discussed to determine the best outcome and how hypertension may be prevented, along with achieving a normalized BMI [44–47].

At this point, the results show that the combination of pharmaceutical and non-pharmaceutical direction should be taken into consideration regarding the treatment of hypertension. Antihypertensive treatments may be postponed when there is no healthy lifestyle implementation before the hypertension diagnostic and if the patients are willing to intervene in this matter. In these cases, the cardiologist will make such a recommendation if there are no high cardiovascular risks and if hypertension is not higher than degree 1. Several national epidemiological studies, SEPHAR I-IV, present the preponderance of arterial hypertension as the main cause of cardiovascular mortality. In 2005, the prevalence of arterial hypertension was higher in rural populations and for men (49.47% countryside vs. 41.58% city and 50.17% men vs. 41.11% women). The prevalence in 2011 was the opposite of the previous data, with most hypertensive patients coming from the city (59.59%), and the number of female patients was higher (54.9%) [48,49]. However, our study focused on the impact of interventional programs upon mixed groups in regard to gender and social environment.

Both physical therapy and hydrotherapy registered significant results, but between the two interventional programs, there are no significant differences at this point. We managed to improve cardiovascular health by increasing calorie burn with these programs based on time efficiency, variety and flexibility. In addition, a full-body workout has an afterburn effect, so calories continue to be burnt even after the session.

An unexpected outcome is to be taken into consideration for the hydrotherapy program, which registered better results for weight loss and diastolic blood pressure compared to all other groups, even compared to the program with physical therapy. Exercises in the pool provide a full-body workout and have a bigger impact on the cardiovascular system without putting stress on the body. If the hydrotherapy program can sustain a better outcome in regard to improving cardiovascular strength, in comparison with the physical program, further investigation and a more detailed analysis need to be performed in order to confirm this theory.

Worldwide, in 2019, around 18.6 million deaths were allocated to CVDs [50]. One year later, in 2020, the numbers increased, reaching 19.1 million deaths due to CVDs. The rise continued, and in 2021, there were 20.5 million registered deaths due to cardiovascular diseases. We must underline the fact that the number-one disease responsible for 60% of CVDs and around 50% of coronary heart disorders is hypertension. Increased BMI was registered for 2.4 million people globally [51]. Intervention is imminent because the predictive statistics data show a continuous increase for BMI, until 2030, for most of the world's population.

The study has several limitations. Firstly, it used a small sample size of patients (*n*. 25 for each group) from a restricted area. The reason for not including social factors in the baseline was that it would limit the number of participants further; maintaining homogeneity within groups would have been challenging with more criteria included. As a result, an analysis that relied on social factors was not taken into consideration at this point. Our study did not prioritize gender analysis, and as the study progressed, we came to realize that it was not relevant because gender homogeneity was only achieved at the intergroup level; intragroup patients were 64% women and 36% men. While analyzing waist circumference separately for men and women would have been more substantial,

our findings indicate that interventional programs have decreased values, resulting in diminished cardiovascular risk. Current research has led to this limitation, but extent research should emphasize gender differences. Additionally, physical and hydrotherapy programs implemented should be tailored to the effort capacity of each gender. Secondly, the 8-week period may be short according to some points of view, especially for the implementation of a healthy lifestyle, where patients had full control over the rate of accomplished tasks. Future studies should have extended follow-ups to sustain this study's outcomes. Lastly, more parameters may also be pursued regarding overweight and hypertension markers. Despite this limitation, our findings underscore the importance of supervised physical activity programs to control BMI, waist circumference and blood pressure values, thus contributing to lowering CVD risks.

5. Conclusions

Our study revealed improvements in BMI, waist circumference and blood pressure values after both physical therapy and hydrotherapy programs. Controlled and guided physical therapy and hydrotherapy had better outcomes compared to the recommendations for a healthy lifestyle alone, even when patients needed to do programs by themselves, unsupervised. The recommendations for a healthy lifestyle as a single method of treatment did not bring significant benefits and is not enough, but when associated with antihypertensive medication, improvements in SBP values were noticed. At this point, we give credit to medication for the progress. Hydrotherapy programs were more efficient in lowering three parameters (BMI, SBP and DBP) than the single physical program, but the results were not statistically significant, so an expendability of the research is needed in this direction to determine which therapeutic intervention or combination of interventions is more effective in lowering the parameters and diminishing cardiovascular risks.

Author Contributions: Conceptualization R.C.R.B., E.G.P., A.O.D., R.M.M. and M.A.; methodology, R.C.R.B., E.G.P. and A.O.D.; software, R.C.R.B., E.G.P. and A.O.D.; validation, R.C.R.B., E.G.P., A.O.D., R.M.M. and M.A.; resources, R.C.R.B., E.G.P. and M.A.; data curation, R.C.R.B., E.G.P. and A.O.D.; writing—original draft preparation, R.C.R.B.; writing—review and editing, R.C.R.B., E.G.P. and M.A.; visualization, R.C.R.B., E.G.P., A.O.D., R.M.M. and M.A.; supervision, R.C.R.B., E.G.P. and M.A. All authors have read and agreed to the published version of the manuscript.

Funding: We would like to acknowledge VICTOR BABES UNIVERSITY OF MEDICINE AND PHARMACY TIMIȘOARA for their support in covering the costs of publication for this research paper.

Institutional Review Board Statement: The study was designed and conducted in accordance with international ethical standards on biomedical research with human beings, The Helsinki Declaration, and approved by the Scientific Research Ethics Committee from Medicine department of University of Medicine and Pharmacy Victor Babeș, Timisoara, Romania. (Approval No. 01, Approval date: 9 January 2023).

Informed Consent Statement: Written informed consent has been obtained from the patient (s) to publish this paper.

Data Availability Statement: The data that support the findings of this study are available on reasonable request from the corresponding author R.C.R.B, upon reasonable request. The data are not publicly available due to privacy and ethical restrictions.

Acknowledgments: We would like to thank all study participants for their implication in the program and assessments. Furthermore, we thank to the cardiologist's offices for their commitment to this study and organizational support during recruitment and to the facilities that sustained the rehabilitation programs.

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

Abbreviations

The following abbreviations are used in this manuscript:

BMI	body mass index
Wcir	waist circumference
SBP	systolic blood pressure
DBP	diastolic blood pressure
NCDs	noncommunicable diseases
CVDs	cardiovascular diseases

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Effectiveness of Home-Based Stretching and Strengthening Training for Improving Flexibility, Strength, and Physical Function in Older Adults with Leg Tightness and/or Suspected Sarcopenia

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Abstract: Background/Objectives: The aim of the present study was to assess the effectiveness of flexibility or strengthening exercises to improve flexibility, strength, muscle architecture, and functional performance in older adults with leg tightness and/or suspected sarcopenia. Methods: Ninety adults with leg tightness and/or suspected sarcopenia (age: 66.8 ± 4.9 years) were randomly allocated to two subtypes of intervention at home: resistance-band exercise (RE) or eccentric exercise (ECC) for those with weakness; static or dynamic stretching for those with tightness; and static stretching plus ECC or no exercise for those with both muscle tightness and weakness. The program consisted of 3–6 weekly sessions over eight weeks. Blinded outcome assessments before and after the eight-week program and at the three-month follow-up included mobility performance via Timed Up-and-Go (TUG), and flexibility and strength tests, as well as measurement of stiffness. Results: All groups had increased peak torque after eight weeks and improved TUG at the three-month follow-up ($p < 0.05$). Improved plantar flexor strength persisted at the three-month follow-up ($p = 0.009$). In addition, the RE and ECC groups had increased muscle thickness by 4.0 and 8.7% after eight weeks ($p < 0.05$). Hamstring flexibility increased in all exercise groups, except the RE group. Moreover, all six groups showed improved calf flexibility, whereas no changes in stiffness were noted. Conclusions: Increases in mobility performance, strength, and flexibility appeared due to learning effects and increased physical activity, rather than the specific training impact. However, strength-based programs may be recommended for older adults with suspected sarcopenia, as they provide additional benefits, such as short-lasting muscle hypertrophy.

Keywords: home-based exercise; stretching; eccentric exercise; Timed Up-and-Go; muscle thickness; stiffness

1. Introduction

A decrease in physiological function is an inevitable aspect of aging. Currently, no definitive strategy has been identified to counteract its effects fully. Several factors contribute to functional decline in older adults, including mitochondrial dysfunction, telomere damage, epigenetic dysregulation, DNA damage, and lipid accumulation [1–3]. Changes in these molecular factors may be precipitated by a sedentary lifestyle, and may contribute to a loss of strength, aerobic endurance, and mobility [4]. Age-associated loss of muscle mass, which is known as sarcopenia, is one of the main contributing factors to muscle weakness. Sarcopenia is also a major consequence of chronic diseases, and results in disability and loss of independence [5]; moreover, it is associated with increased all-cause mortality [6]. In addition to muscle weakness, an age-related decline in flexibility can be attributed to several factors, including collagen cross-linking, increases in intramuscular adipose tissue and extracellular water content, and a reduction in collagen fibril diameter [7–9].

Exercise may mitigate this physical degeneration associated with aging, and sarcopenia can be effectively managed through resistance-based exercise. Home-based resistance exercises using elastic bands have been shown to improve lean mass, strength, and muscle quality in older adults [10]. Eccentric exercise, which involves muscle lengthening under load, is particularly advantageous for the elderly because of its lower metabolic cost and perceived effort, despite higher training loads. In fact, even low-intensity, no-equipment eccentric muscle contractions are more effective than concentric training in enhancing physical function and health [11]. Moreover, resistance exercises performed across a wide range of motion (ROM), including eccentric training, have been demonstrated to offer additional benefits in terms of flexibility [12–14].

In contrast to resistance exercises, which primarily enhance muscle strength, flexibility is predominantly improved through stretching interventions. Both acute and chronic static stretching have been shown to increase ROM in older adults [15,16]. These improvements may be partly attributed to reductions in musculotendinous unit (MTU) stiffness and muscle or nerve stiffness, and/or increased fascicle length [17–19]. Stretching, particularly when combined with rhythmic movements, may offer additional benefits, such as enhanced balance [20,21] and physical function [19,22]. For example, dynamic hamstring stretching involving seven repetitions resulted in a 45% improvement in hamstring flexibility, a 10% increase in knee strength torque, and a 14.3% reduction in the time to complete the Timed Up-and-Go test among older women [22].

Home-based exercise represents a practical and cost-effective approach to improve health, and provides a safe and feasible solution for older adults [23,24]. As noted, older adults may experience either singular or multiple impairments, and individualized supervised exercise training targeting specific issues could offer additional benefits beyond the primary objectives. Despite these advantages, there remains limited evidence regarding the effectiveness of home-based flexibility or strengthening exercises on outcomes such as muscle architecture, flexibility, MTU stiffness, strength, and functional performance in older adults with muscle weakness and/or tightness. The aim of this study was to address this gap by evaluating whether home-based flexibility exercises (static stretching) or strengthening exercises (eccentric training) produce greater improvements in these outcomes than dynamic stretching or elastic-band strengthening. Our hypothesis was that both types of home-based exercise would improve flexibility, muscle ultrasound measures, and strength. Additionally, we expected that individuals with multiple weaknesses would tend to have lower mobility, and would experience greater improvements in functional performance when participating in programs targeting both strength and flexibility. This knowledge allows for the implementation of more tailored and effective treatment strategies, thus

optimizing their outcomes for older adults with varying degrees of muscle weakness or tightness.

2. Materials and Methods

2.1. Participants

Older adults of both genders, aged between 60 and 75 years old, who were experiencing muscle tightness and/or weakness were recruited into this study (mean age, 66.8 $\pm$ 4.9 years; BMI, 23.1 $\pm$ 3.9 kg·m^{-2}). Figure 1 depicts the CONSORT flow diagram of the study, showing the formation of six subgroups, culminating in a total of 90 older adults with muscle tightness and/or weakness. Participants were recruited via advertainments from Chonburi Province, including the areas of Seansuk, Mueang, and surrounding communities. The inclusion criteria were as follows: individuals who were categorized as "low active" (engaging in less than 150 min of moderate physical activity level per week), had a BMI of less than 30 kg·m^{-2}, and passed the Physical Activity Readiness Questionnaire. Individuals with hamstring muscle tightness were identified as having a result of $\leq$80° on a passive straight-leg raise (SLR) test [25]. Those with generalized muscle weakness, which is potentially indicative of sarcopenia, were identified based on a calf circumference of less than 34 cm for males and less than 33 cm for females, or a Simple Questionnaire to Rapidly Diagnose Sarcopenia (SARC-F) score of $\geq$4. Moreover, a handgrip strength of below 28 kg for males and below 18 kg for females was used in this context, according to the guidelines of the Asian Working Group for Sarcopenia 2019 [26]. The exclusion criteria were as follows: uncontrolled hypertension or diabetes mellitus, decompensated heart failure, severe kidney disease, severe peripheral artery disease, neurological conditions that could interfere with exercise, abnormal electrocardiography findings, significant lower-body injuries within the past six months (e.g., fractures, dislocations, ruptures, and joint replacements), dependence on walking assistance, a history of lower-body pain exceeding 5/10 on the visual analog scale within the past six months, participation in stretching and resistance exercises in the preceding three months, treatments that could affect hemodynamic responses or muscle function, or missing more than 20% of the scheduled training sessions. All participants were provided with detailed information regarding the study protocol, and gave written informed consent before their participation. The study protocol received approval from the Research and Innovation Administration Division of the Burapha University Ethics Committee (IRB1-076/2566), in accordance with the principles outlined in the Declaration of Helsinki.

2.2. Study Design

Initially, the participants were familiarized with the testing apparatus at the Allied Health Science Faculty, Burapha University, 2–3 days before the baseline measurements were taken. The assessments were conducted in a specified order on the right leg, and included evaluations of muscle (body mass, biceps femoris [BF], vastus lateralis [VL], medial gastrocnemius [MG]) morphology, leg flexibility, musculotendinous unit (MTU) stiffness, leg muscle strength, and the Timed Up-and-Go (TUG) test. Measurements were collected at baseline, after an eight-week training protocol, and at the three-month follow-up. All assessments were performed by the same skilled and blinded investigators, to ensure consistency. The reliability of these measurements has been demonstrated in a previous study [19].

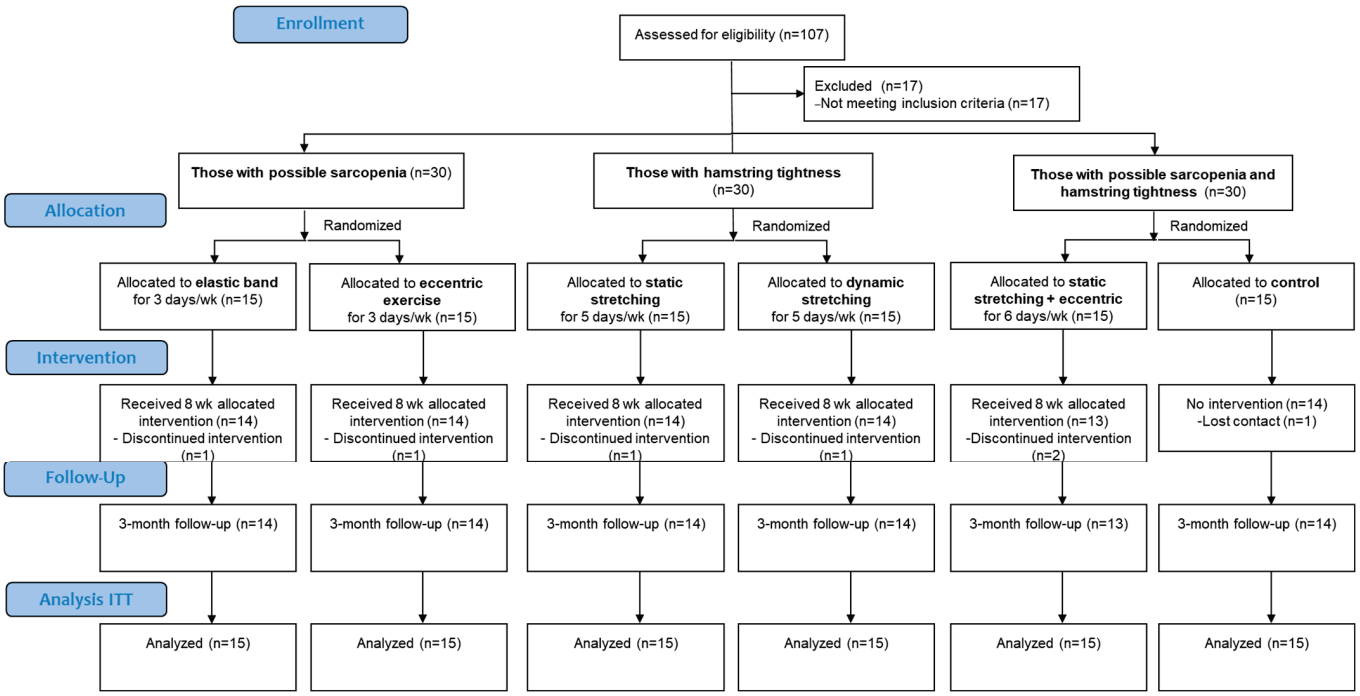


Figure 1. CONSORT diagram of study.

Participants in the groups with matched conditions (muscle tightness, muscle weakness, and both tightness and weakness) were randomly assigned to one of the subtypes of exercise intervention corresponding to each condition. Randomization was achieved using sequentially numbered, opaque, and sealed envelopes. The exercise interventions were as follows: home-based resistance-band exercise (RE) or eccentric exercise (ECC) for those with muscle weakness; home-based static stretching (SS) or dynamic stretching (DS) for those with muscle tightness; and a home-based combination of static stretching with eccentric exercise (SS + ECC) or an educated control condition (CON) for those with both muscle tightness and weakness.

During the first week of the exercise program, the participants met at the laboratory to perform exercises collectively, receive training on safety protocols, and learn how to monitor the signs of safety and progress while exercising at home. Each session commenced with a 7 min warm-up that involved self-paced walking. The exercise regimen consisted of 3–6 sessions per week over eight weeks, and targeted both legs. The home-based exercise protocols were detailed in a booklet using written and visual instructions, and the participants were provided with an exercise diary for program tracking. Research assistants engaged in real-time video calls at least once per week to supervise the home exercises, and the participants were required to attend laboratory sessions at least twice during the three-month follow-up period to discuss progress and their continuous engagement with the exercise sessions of the home program. After a three-month unsupervised period, all participants were asked to record the number of continuous sessions of exercise training in which they continued to engage. This study protocol was registered as a clinical trial (TCTR20240605001) "www.thaiclinicaltrials.org (accessed on 12 January 2025)".

2.3. Interventions

2.3.1. Home-Based Resistance-Band Training

The exercise program, which was designed based on the study reported by Nilsson et al. [10], consisted of the following three lower-body exercises: knee extension, knee

flexion, and plantar flexion, which were all performed in a seated position. Each exercise was conducted with controlled movements, emphasizing a slow pace and a wide range of motion, while in a seated position. The participants performed 3 sets of 15 repetitions per exercise, with a 1 min resting interval between sets. Moreover, the participants were instructed individually regarding the use of the Rate of Perceived Exertion (RPE) scale, which is based on Borg's original scale, and a metronome was provided to them to aid in maintaining the exercise tempo. The exercise intensity was progressively increased over the eight-week period; initially, the intensity was low (RPE: 6–11) in the first two weeks, subsequently advancing to a moderate intensity (RPE: 12–17) for 3rd–6th weeks, and ultimately to a high intensity (RPE: >18) in the last two weeks [11]. The bands were available in various resistances: yellow (1.32 kg), red (1.77 kg), green (2.27 kg), blue (3.22 kg), and black (4.40 kg). The tension was increased gradually throughout the study, to ensure continued adaptation. The participants engaged in the exercise program three times per week, on nonconsecutive days, for a total duration of eight weeks.

2.3.2. Home-Based Eccentric Training

The training program was executed in three standing positions: one-leg squat, single-leg Romanian deadlift T-drop, and calf down with chair or wall support. This regimen was based on previous studies [11,27,28]. Specifically, the single-leg Romanian deadlift T-drop targeted the hamstrings [27], whereas the one-leg squat and calf down exercises addressed the knee extensors and ankle plantar flexors, respectively. To control the ROM during exercise, the single-leg Romanian deadlift T-drop began with the knee flexed at 10–15°, with the individual gradually leaning forward until reaching the maximum hip flexion ROM. The one-leg squat was performed slowly, with the knee bending to achieve 90° of flexion. The single calf down started from maximum plantar flexion and slowly descended to the endpoint of dorsiflexion. The exercises were performed using controlled movements, emphasizing slow and precise technique, for 3 sets of 15 repetitions each, with a 1 min resting interval between sets. The exercise intensity was progressively increased based on the RPE scale, as described previously. The program's progression involved the optional use of a backpack for additional weight, to enhance intensity further [28]. The participants performed the training program three times per week on nonconsecutive days, over an eight-week period.

2.3.3. Home-Based Static Stretching

After a standardized warm-up, the participants performed the stretching exercises as follows. For the knee extensors, the participants stood on one leg, using a wall or a chair for support. They were instructed to grasp the contralateral ankle while fully flexing the knee, and to increase hip extension if maximum tension of the knee extensors had not been achieved. For the knee flexors, the participants raised their leg with the knee kept straight and placed it on a chair or table. The stretch was maintained by making slight adjustments to the hip flexion angle, to ensure optimal stretching [29]. For the ankle plantar flexors, the participants began by standing on both legs, then stepped the leg to be stretched backward, while keeping the knee straight. The heel of the foot was allowed to contact the floor, with the contralateral knee slightly bent, to enhance the stretch. All stretching exercises were held at a constant maximum tension, ensuring that no pain was experienced while the muscles were relaxed as much as possible, for a duration of 30 s per stretch. Each stretch was performed 8 times, with a 15 s resting interval between repetitions. This stretching regimen was performed five times per week over a period of eight weeks.

2.3.4. Home-Based Dynamic Stretching

After a standardized warm-up, the dynamic stretching exercises for the leg muscle groups were performed as follows. For the knee extensors, the participants performed the stretch in a standing position. They grasped the ankle of the involved leg while maintaining full knee flexion, then actively extended the hip to deepen the stretch. For the knee flexors, a closed kinetic chain hamstring stretch was employed, as described by Chen et al. [30]. The participants stood on the involved leg with the knee slightly flexed (10–15°), and leaned forward slowly until they reached the end of the hip flexion ROM. To maintain spinal alignment and balance, the contralateral leg was lifted into hip extension. The participant alternated between bending and extending the knee for 2 s each, thereby stretching the hamstring muscles. The intensity of the stretch was adjusted by modifying the forward-leaning angle of the trunk. For the calf muscles, the participants stood with one leg positioned at the edge of a stair, keeping the knee straight and allowing the heel of the foot to extend beyond the edge. They then alternated between performing ankle dorsiflexion while bending the contralateral knee. To enhance stability during the exercises, the participants used the back of a chair or a wall for support, especially during one-legged stances and forward-leaning positions. Each stretching exercise was performed until maximum tolerable tension was achieved without causing pain, and the exercises were repeated 15 times, for a total of 30 s, with continuous motion, using 8 sets, with a 15 s break between sets. The program was executed 5 times per week over eight weeks.

2.3.5. Home-Based Static Stretching Plus Eccentric Exercise

After a standardized 7 min warm-up, the participants engaged in a structured exercise regimen consisting of static stretching and eccentric exercises. The program was designed to alternate between these two types of exercises, with the participants performing static stretching and eccentric exercises on separate days. Specifically, the participants completed static stretching for 3 days per week and eccentric exercises for 3 days per week, resulting in a total of 6 exercise sessions per week. This schedule was maintained for eight weeks.

2.3.6. Control

The participants included in this group received information on general exercise recommendations for older adults, as outlined by the American College of Sports Medicine (ACSM) guidelines 2022. Moreover, the participants were asked to document their weekly physical activity levels in a booklet that was provided to them.

2.4. Outcome Measures

2.4.1. Handgrip Strength

Handgrip strength assessment was used only for screening individuals with suspected sarcopenia, as it is commonly employed for this purpose. Handgrip strength assessment is commonly employed as a measure of maximum grip strength. In this study, a Baseline Hydraulic Hand Dynamometer (Fabrication Enterprises Inc., New York, NY, USA) was used to evaluate grip strength. Participants were seated with their arms extended in a neutral position, and were instructed to squeeze the dynamometer with maximal effort for a duration of 2–3 s. Three separate grip strength measurements were recorded for each participant, and the mean value of these measurements was calculated and used for subsequent analysis [10].

2.4.2. Body Mass

Body mass was assessed using a BC-705N WH Tanita Body Composition Monitor (Tanita Corporation, Tokyo, Japan) at three time points: at the baseline, after an eight-week training protocol, and at the three-month follow-up.

2.4.3. Timed Up-and-Go Test

The physical mobility performance was assessed by the TUG test [31], which measures the time that is required for a participant to stand up from an armchair, walk a distance of 3 m, navigate around a cone, and return to a sitting position on the chair. The setup of this test includes a firm chair with arms (seat height, 46 cm) and a cone placed 3 m away from the chair. The test procedure began with the participant seated in the chair with their back against the backrest, arms resting on their lap, and feet positioned just behind the distance marker on the floor. The participants received the following instructions: "On the word 'go', stand up, walk comfortably and safely to the cone on the floor, walk around the cone, return to the chair, and sit back down". Timing started on the word "go" and stopped when the participant's back rested against the chair upon returning. Each participant first completed a practice trial, followed by two recorded trials. The data from the two recorded trials were averaged for use in the data analysis [32].

2.4.4. Muscle Architecture

B-mode ultrasonography was employed to capture muscle images of the right leg, using an M5 series ultrasound system (Shenzhen Mindray Bio-Medical Electronics, Shenzhen, China) with a linear 4 cm, 7.5 MHz probe (MSK preset). The ultrasound probe was positioned 15 cm above the popliteal line, with the participant in a relaxed prone position. For the BF muscle, images were captured in the longitudinal view, both at rest and at the endpoint of passive SLR procedures. This was carried out using a thin layer of ultrasound gel and minimal pressure applied by the probe. The thickness of the VL muscle was measured at the same thigh level in the supine position, using transverse imaging. The MG muscle was also imaged longitudinally, both at rest and at the endpoint of a passive ankle dorsiflexion test. For these measurements, the ultrasound probe was positioned 10 cm below the popliteal line. For each muscle, transverse views were also captured to assess echo intensity (EI), and each location was imaged twice. The ultrasound settings were kept consistent across participants, with a frequency of 10 MHz, the gain set at 54 dB, a dynamic range of 60 dB, and a depth of 5 cm. Muscle thickness (MT) was analyzed, with MT defined as the distance between the superficial and deep aponeuroses. Fascicle length (FL) was estimated by extrapolating the visible fascicles between the superficial and deep aponeuroses using Tracker 6.2.0 "https://opensourcephysics.github.io/tracker-website/ (accessed on 12 January 2025)" [33]. For each muscle, the averages of two images for MT and FL were calculated and used for further analysis.

2.4.5. Flexibility

Leg flexibility measurements were performed as described in our previous study [19]. Hamstring flexibility was assessed using a passive SLR with a bubble inclinometer (Baseline, Fabrication Enterprises, Elmsford, NY, USA). The maximum angle recorded by the inclinometer was noted, and a longitudinal image of the BF muscle was captured using ultrasound. Calf flexibility was evaluated through passive ankle dorsiflexion (PDF) in a prone position, using a standard goniometer (Mahidol University, Bangkok, Thailand). Each test was performed three times, with a 15 s resting interval between attempts. The average of the two closest angles was used for further analysis.

2.4.6. Passive MTU Joint Stiffness

A Biodex System 4 isokinetic dynamometer (Biodex Medical Systems, Inc., Shirley, NY, USA) was utilized for the passive assessment of MTU properties. The setup, testing protocol, and analytical procedures used for knee flexors and ankle plantar flexors were as delineated in our previous study [19]. In this study, a minor modification was made to the ROM testing for plantar flexor MTU stiffness: the ankle was positioned from 30° of plantar flexion to an endpoint of 30° dorsiflexion while seated. Passive stiffness was determined from the slope of the passive torque–angle relationship, corrected for the weight of the lower leg, by analyzing the increase in passive torque between 50 and 80% of the maximum ROM using a least-squares method [29,34].

2.4.7. Leg Muscle Strength

Leg muscle strength was assessed in the right leg using a Biodex System 4 dynamometer (Biodex Medical Systems, Inc., Shirley, NY, USA), at a sampling rate of 100 Hz. Before the maximum isometric voluntary contraction (MIVC) procedure, the participants were secured in the dynamometer chair, and performed warm-up contractions at 50% of maximal effort for 2–3 repetitions, followed by a 2 min resting period. For the testing of knee extensors and flexors, the participants were positioned with the hip flexed to 85°, and the knee flexed to 70° for extensors and 50° for flexors. For ankle plantar flexion, the participants were seated with the hip flexed to 85°, the knee slightly bent at 10°, and the ankle in a neutral position (0°) [35]. During the MIVC, the participants were encouraged to "exert maximal force as hard as possible and hold for 3 s", with each contraction repeated after a 1 min resting interval. The peak torque of each MIVC was recorded and analyzed for further evaluation.

2.4.8. Level of Satisfaction with Exercise Program

The participants provided ratings of their satisfaction with the exercise program after eight weeks of training, using a Likert scale ranging from +3 to −3. On this scale, +3 denotes "extremely satisfied" and −3 indicates "very dissatisfied".

2.5. Statistical Analysis

From the preliminary study, we determined that a sample size of 10 subjects per group would be sufficient to detect muscle strength differences with a statistical power of 80%, assuming a significance level of $p < 0.05$ and an effect size greater than 0.8. The sample size was subsequently increased by 50% (N = 15) in each group to account for expected dropout events. Similarly, Tarnopolsky et al. [36] suggested that a sample size of 10 participants per group is adequate to detect differences in body composition and strength.

Descriptive data are presented as the mean ± SD and median (IQR), where appropriate. Data were initially assessed for normality using the Shapiro–Wilk test. Most data exhibited a normal distribution, except for the SLR and PF MTU stiffness tests. One-way analysis of variance (ANOVA) or the Kruskal–Wallis test was used to compare baseline measurements and characteristics among the groups. An intention-to-treat approach was employed, with time and group effects analyzed using a mixed ANOVA [time (pre-, post-eight weeks of training, post-three-month follow-up) × group (five interventions and control)], encompassing the six interventions and each study arm of the three conditions. Additionally, two-way ANOVAs (time × intervention) were conducted separately for each arm of the three conditions. Post hoc multiple comparisons were conducted using the Bonferroni correction for significant interactions. The effect size (ES) was reported as the partial eta-squared for repeated measures [37], and as a Cohen *d* when the pairwise

comparison was performed [38]. Statistical significance was set at an alpha level of 0.05. All statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS) for Windows, version 24.0 (IBM Corp., Armonk, NY, USA).

3. Results

Compliance with training session attendance is illustrated in Figure 1. The baseline characteristics of the participants are detailed in Table 1. The RE and ECC groups had a lower proportion of men than the remaining groups ($p < 0.001$). Moreover, the participants in the SS group had a larger body mass than the RE and ECC groups ($p = 0.013$), and the participants in the SS and DS groups were taller than those in the ECC group ($p = 0.04$). In addition, the pre-intervention values for handgrip strength and SLR amplitude, the two indices used in selection for weakness and allocation into groups, exhibited substantial differences across the six groups, and resulted in different male/female (M/F) representation in each group.

Table 1. Characteristics of participants.

	RE (N = 15)	ECC (N = 15)	SS (N = 15)	DS (N = 15)	SS + ECC (N = 15)	CON (N = 15)	*p*-Value
Gender (M/F)	1/14	1/14	9/6 [r,e]	8/7 [r,e]	6/9 [r,e]	4/11 [r,e]	<0.001
Age (years)	66.1 ± 4.7	67.5 ± 3.2	68.3 ± 4.3	65.9 ± 4.7	65.9 ± 3.9	66.9 ± 2.8	0.470
Body mass (kg)	55.1 ± 6.6 [s]	52.8 ± 4.2 [s]	65.2 ± 8.8	60.3 ± 10.2	55.8 ± 7.6	61.3 ± 14.3	0.004
Height (cm)	155.3 ± 6.0	153.9 ± 5.8	162.5 ± 9.2 [e]	162.6 ± 7.4 [e]	159.6 ± 7.4	159.1 ± 8.9	0.007
BMI ($kg \cdot m^{-2}$)	22.9 ± 3.0	22.4 ± 1.8	24.7 ± 2.8	22.7 ± 2.6	21.9 ± 2.2	24.0 ± 3.9	0.062
PA volume ($min \cdot wk^{-1}$) *	60 (150)	180 (240)	0 (210)	0 (90)	140 (200)	100 (375)	0.332
Handgrip strength (kg)	13 (6) [s,d]	14 (4) [s,d]	22 (12)	28 (11)	16 (10) [s,d]	14 (6) [s,d]	<0.001
SLR (deg)	92 (14)	85 (9)	75 (9) [r, e]	71 (9) [r,e]	68 (11) [r,e]	72 (9) [r,e]	<0.001

Data are mean ± SD, and median (interquartile range) for exercise volume, handgrip strength, and SLR. BMI, body mass index; PA, physical activity; RE, home-based resistance-band exercise; ECC, eccentric exercise; SS, static stretching exercise; DS, dynamic stretching exercise; CON, control; SLR, straight-leg raise. [r] significantly different from RE; [e] significantly different from ECC; [s] significantly different from SS; [d] significantly different from DS (all $p < 0.05$). * PA volume was recorded through self-reports, regardless of intensity of activity.

3.1. Differences Between Groups at Baseline

The thickness of the BF muscle in the SS group was larger than that of the CON group ($p = 0.034$). Moreover, the resting and lengthened FLs of the BF muscle were greater in the RE group than in the CON group ($p < 0.01$). Furthermore, the FL of the MG in the SS group was greater than that in the CON group ($p < 0.05$). Participants with possible sarcopenia (i.e., those in the RE and ECC groups) exhibited a greater KF MTU compliance than those in the SS and DS groups ($p < 0.05$). In addition, there were differences among the groups regarding the normalized MIVC of the KE and KF muscles when adjusted for body mass, with the DS group exhibiting greater muscle strength than the RE group ($p < 0.05$). These differences were likely due to different representations of genders between groups.

3.2. Responses to Interventions

Body mass remained consistent across all groups throughout the study. Using an ITT approach with a mixed ANOVA, a substantial change in the results of the TUG test was observed over time [$F(2,168) = 15.8$, $p < 0.001$, $\eta_p^2 = 0.16$], without group effects and interaction. Specifically, the improvement in TUG performance was similar in all groups at the three-month follow-up, compared with the performance both pre-training and after eight weeks of training (0.34 and 0.23 s on average, respectively; $p \leq 0.001$) (Table 2). In the analysis within each arm, an interaction effect for the stretching intervention [$F(2,56) = 4.3$, $p = 0.018$, $\eta_p^2 = 0.13$] was observed, indicating differences in change functional mobility

between the SS and DS (d = 0.91, p = 0.003) groups after 8 weeks of training (Table 2), even though overall improvement was similar across groups after the 3-month follow-up.

Table 2. Changes in Timed Up-and-Go (TUG) test performance and normalized maximum isometric voluntary contraction with interventions.

	RE (N = 15)	ECC (N = 15)	SS (N = 15)	DS (N = 15)	SS + ECC (N = 15)	CON (N = 15)
TUG (s) Time effect (p < 0.001); **i**nteraction effect (p = 0.125); **g**roup effect (p = 0.154)						
Pre-	6.91 ± 1.03	6.65 ± 0.63	6.40 ± 1.11	6.45 ± 0.81	6.30 ± 0.80 ^{G}	6.80 ± 0.86 ^{G}
Post-8 wk	7.15 ± 0.91	6.51 ± 0.37	6.34 ± 1.23	5.82 ± 0.56 ^{T}	6.00 ± 0.76	6.77 ± 1.04
F/U 3 mo	6.62 ± 1.20 ^{T}	6.28 ± 0.63 ^{T}	6.03 ± 1.14 ^{T}	5.86 ± 0.70 ^{T}	5.92 ± 0.66 ^{T}	6.34 ± 0.65 ^{T}
Each arm	T_{effect} (p = 0.007) I_{effect} (p = 0.176) G_{effect} (p = 0.159)		T_{effect} (p = 0.002) I_{effect} (p = 0.018) G_{effect} (p = 0.418)		T_{effect} (p = 0.010) I_{effect} (p = 0.645) G_{effect} (p = 0.029)	
MIVC KE (Nm/BW) Time effect (p = 0.001); **i**nteraction effect (p = 0.185); **g**roup effect (p = 0.024)						
Pre-	1.53 ± 0.41	1.67 ± 0.37	1.80 ± 0.53	2.07 ± 0.39	1.87 ± 0.42 ^{G}	1.80 ± 0.37 ^{G}
Post-8 wk	1.68 ± 0.33 ^{T}	1.85 ± 0.49 ^{T}	2.04 ± 0.63	2.11 ± 0.45	2.14 ± 0.38 ^{T}	1.74 ± 0.29
F/U 3 mo	1.74 ± 0.23	1.80 ± 0.51	1.87 ± 0.57	2.06 ± 0.36	2.09 ± 0.35	1.72 ± 0.29
Each arm	T_{effect} (p = 0.017) I_{effect} (p = 0.586) G_{effect} (p = 0.443)		T_{effect} (p = 0.057) I_{effect} (p = 0.264) G_{effect} (p = 0.307)		T_{effect} (p = 0.123) I_{effect} (p = 0.006) G_{effect} (p = 0.020)	
MIVC KF (Nm/BW) Time effect (p = 0.005); **i**nteraction effect (p = 0.468); **g**roup effect (p = 0.005)						
Pre-	0.62 ± 0.17	0.70 ± 0.16	0.78 ± 0.25	0.88 ± 0.19	0.80 ± 0.15 ^{G}	0.69 ± 0.17 ^{G}
Post-8 wk	0.65 ± 0.11	0.76 ± 0.08	0.86 ± 0.31	0.89 ± 0.22	0.91 ± 0.13	0.70 ± 0.14
F/U 3 mo	0.71 ± 0.16 ^{T}	0.77 ± 0.11 ^{T}	0.87 ± 0.36	0.86 ± 0.22	0.88 ± 0.17	0.69 ± 0.18
Each arm	T_{effect} (p = 0.006) I_{effect} (p = 0.655) G_{effect} (p = 0.065)		T_{effect} (p = 0.368) I_{effect} (p = 0.244) G_{effect} (p = 0.668)		T_{effect} (p = 0.052) I_{effect} (p = 0.138) G_{effect} (p = 0.002)	
MIVC PF (Nm/BW) Time effect (p = 0.001); **i**nteraction effect (p = 0.216); **g**roup effect (p = 0.111)						
Pre-	1.34 ± 0.29	1.38 ± 0.26	1.23 ± 0.33	1.39 ± 0.43	1.34 ± 0.31 ^{G}	1.25 ± 0.32 ^{G}
Post-8 wk	1.44 ± 0.37	1.39 ± 0.27	1.22 ± 0.32	1.59 ± 0.36 ^{T}	1.52 ± 0.25	1.31 ± 0.21
F/U 3 mo	1.47 ± 0.39	1.44 ± 0.41	1.41 ± 0.44 ^{T}	1.58 ± 0.35 ^{T}	1.49 ± 0.30	1.29 ± 0.19
Each arm	T_{effect} (p = 0.261) I_{effect} (p = 0.669) G_{effect} (p = 0.842)		T_{effect} (p = 0.002) I_{effect} (p = 0.073) G_{effect} (p = 0.071)		T_{effect} (p = 0.136) I_{effect} (p = 0.618) G_{effect} (p = 0.017)	

Data are mean ± SD. RE, home-based resistance-band exercise; ECC, eccentric exercise; SS, static stretching exercise; DS, dynamic stretching exercise; SS + ECC, static stretching with eccentric exercise; CON, control; MIVC, maximal isometric voluntary contraction; KE, knee extensor; BW, body weight; KF, knee flexor; PF, plantar flexor. ^{T} Significant difference from pre-measurement for each study arm analysis. ^{G} Significant difference between exercise interventions for each study arm analysis. All p < 0.05.

Regarding changes in muscle strength, there was no significant interaction for the normalized MVC of the three muscle groups. However, there was a significant main effect of time for the KE [F(2,168) = 7.7, p = 0.001, η_p^2 = 0.08], KF [F(2,168) = 5.6, p = 0.005, η_p^2 = 0.06], and PF [F(2,168) = 8.3, p < 0.001, η_p^2 = 0.09] torque, as well as a group effect for the KE [F(5,84) = 2.8, p = 0.024, η_p^2 = 0.14] and KF [F(5,84) = 3.6, p = 0.005, η_p^2 = 0.18] torque. Moreover, there was an increase in peak torque for all three muscles after the eight-week training period in all groups, and these changes persisted in the PF muscle at the three-month follow-up (p = 0.009), as presented in Table 2. Within each study arm, similar changes in peak torque were observed between interventions—except for the comparison between the SS + ECC and CON groups, which revealed an interaction and group effect for KE (d = 0.81; p = 0.004 for the SS + ECC group), and group effects for KF and PF torque, as presented in Table 2.

In terms of muscle size, no significant interaction, group, or time effects were observed for the MT of the MG and BF muscles. However, the VL muscle exhibited both an interaction effect [F(10,168) = 2.2, p = 0.018, η_p^2 = 0.12] and a time effect [F(2,168) = 19.2, p < 0.001, η_p^2 = 0.19]. This was reflected by a substantial increase in the VL MT as a result of ECC training (d = 0.70, p = 0.018) (Table 3); however, no such change was noted in the remaining muscles investigated here, or with other interventions. This adaptation was diminished after the three-month follow-up, as the ECC group exhibited a reduction in the thickness of the VL muscle (d = 0.63, p < 0.05) compared with the measurements collected after

eight weeks of training. A repeated measures ANOVA revealed no significant effects of interaction for MT within the study arms.

Table 3. Changes in muscle thickness and fascicle length with six interventions.

	RE (N = 15)	ECC (N = 15)	SS (N = 15)	DS (N = 15)	SS + ECC (N = 15)	CON (N = 15)
VL MT (cm) **T**ime effect ($p < 0.001$); **i**nteraction effect ($p = 0.018$); **g**roup effect ($p = 0.158$)						
Pre-	1.86 ± 0.27	1.73 ± 0.27	1.98 ± 0.30	1.97 ± 0.39	1.75 ± 0.26	1.75 ± 0.39
Post-8 wk	1.94 ± 0.35 ^{T}	1.88 ± 0.11 ^{T}	2.05 ± 0.32	1.96 ± 0.34	1.83 ± 0.34	1.80 ± 0.29
F/U 3 mo	1.82 ± 0.38	1.59 ± 0.16	1.96 ± 0.27	1.96 ± 0.42	1.77 ± 0.32	1.83 ± 0.25
Each arm	T_{effect} ($p = 0.001$) I_{effect} ($p = 0.105$) G_{effect} ($p = 0.122$)		T_{effect} ($p = 0.507$) I_{effect} ($p = 0.476$) G_{effect} ($p = 0.079$)		T_{effect} ($p = 0.366$) I_{effect} ($p = 0.729$) G_{effect} ($p = 0.920$)	
BF MT (cm) **T**ime effect ($p = 0.232$); **i**nteraction effect ($p = 0.521$); **g**roup effect ($p = 0.003$)						
Pre-	1.61 ± 0.30	1.60 ± 0.30	1.74 ± 0.23	1.69 ± 0.32	1.67 ± 0.24 ^{G}	1.42 ± 0.26 ^{s,G}
Post-8 wk	1.60 ± 0.29	1.53 ± 0.25	1.79 ± 0.35	1.66 ± 0.26	1.63 ± 0.17	1.35 ± 0.23
F/U 3 mo	1.57 ± 0.22	1.48 ± 0.18	1.77 ± 0.22	1.68 ± 0.18	1.62 ± 0.17	1.45 ± 0.25
Each arm	T_{effect} ($p = 0.155$) I_{effect} ($p = 0.558$) G_{effect} ($p = 0.480$)		T_{effect} ($p = 0.892$) I_{effect} ($p = 0.688$) G_{effect} ($p = 0.340$)		T_{effect} ($p = 0.455$) I_{effect} ($p = 0.538$) G_{effect} ($p = 0.001$)	
MG MT (cm) **T**ime effect ($p = 0.980$); **i**nteraction effect ($p = 0.232$); **g**roup effect ($p = 0.248$)						
Pre-	1.56 ± 0.22	1.47 ± 0.17	1.60 ± 0.30	1.60 ± 0.25	1.49 ± 0.25	1.44 ± 0.19
Post-8 wk	1.56 ± 0.25	1.50 ± 0.13	1.61 ± 0.27	1.56 ± 0.27	1.45 ± 0.26	1.54 ± 0.17
F/U 3 mo	1.56 ± 0.21	1.41 ± 0.15	1.64 ± 0.27	1.59 ± 0.27	1.47 ± 0.24	1.50 ± 0.20
Each arm	T_{effect} ($p = 0.159$) I_{effect} ($p = 0.155$) G_{effect} ($p = 0.144$)		T_{effect} ($p = 0.743$) I_{effect} ($p = 0.682$) G_{effect} ($p = 0.733$)		T_{effect} ($p = 0.618$) I_{effect} ($p = 0.122$) G_{effect} ($p = 0.733$)	
BF FL at rest (cm) **T**ime effect ($p = 0.274$); **i**nteraction effect ($p = 0.450$); **g**roup effect ($p = 0.006$)						
Pre-	10.77 ± 2.66	8.99 ± 2.25	8.74 ± 2.32	8.71 ± 1.95	9.63 ± 2.70 ^{G}	7.85 ± 1.98 ^{r,G}
Post-8 wk	10.40 ± 1.86	9.63 ± 2.49	9.54 ± 2.33	9.16 ± 1.66	9.50 ± 1.97	7.53 ± 1.76
F/U 3 mo	10.80 ± 2.20	9.27 ± 1.97	9.30 ± 2.13	9.76 ± 2.11	9.16 ± 1.63	7.62 ± 2.32
Each arm	T_{effect} ($p = 0.904$) I_{effect} ($p = 0.422$) G_{effect} ($p = 0.056$)		T_{effect} ($p = 0.049$) I_{effect} ($p = 0.457$) G_{effect} ($p = 0.988$)		T_{effect} ($p = 0.626$) I_{effect} ($p = 0.833$) G_{effect} ($p = 0.010$)	
BF FL at the end of SLR (cm) **T**ime effect ($p = 0.010$); **i**nteraction effect ($p = 0.036$); **g**roup effect ($p < 0.001$)						
Pre-	16.68 ± 2.35	14.33 ± 3.09	13.86 ± 2.34	12.28 ± 3.01	14.33 ± 2.98 ^{G}	11.47 ± 2.15 ^{G}
Post-8 wk	15.54 ± 2.10	14.49 ± 2.70	14.13 ± 2.54	13.90 ± 3.25 ^{T}	15.32 ± 1.02	11.27 ± 2.00
F/U 3 mo	16.08 ± 2.54	14.41 ± 3.31	15.30 ± 2.33 ^{T}	14.54 ± 3.68 ^{T}	15.48 ± 1.72	11.02 ± 3.01
Each arm	T_{effect} ($p = 0.486$) I_{effect} ($p = 0.269$) G_{effect} ($p = 0.080$)		T_{effect} ($p = 0.001$) I_{effect} ($p = 0.250$) G_{effect} ($p = 0.397$)		T_{effect} ($p = 0.699$) I_{effect} ($p = 0.154$) G_{effect} ($p = 0.001$)	

Data are mean ± SD. RE, home-based resistance-band exercise; ECC, eccentric exercise; SS, static stretching exercise; DS, dynamic stretching exercise; CON, control; VL, vastus lateralis; MT, muscle thickness; BF, biceps femoris; MG, medial gastrocnemius; FL, fascicle length; SLR, straight-leg raise. ^{T} Significant difference from pre-measurement for each study arm analysis. ^{G} Significant difference between exercise interventions for each study arm analysis. ^{s} significantly different from SS. ^{r} significantly different from RE. All $p < 0.05$.

Last, the ultrasound measurements indicated a group effect for the three FL measurements, as observed in the baseline comparisons, independent of time effects. An interaction effect was found to be significant only for the BF FL measured at the end of the SLR test [$F(10,168) = 2.4$, $p = 0.011$, $\eta_p^2 = 0.13$], which was accompanied by a time effect [$F(2,168) = 3.7$, $p = 0.027$, $\eta_p^2 = 0.042$], with a marked increase in the FL in the DS intervention group ($d = 0.77$, $p = 0.001$), as detailed in Table 3. After the three-month follow-up, this change remained significant, with both the SS and DS groups exhibiting an increased FL compared with the pre-training measurements ($d = 0.82$, 0.90; all $p < 0.01$). When comparing each study arm, the results were similar across the six interventions, with changes only observed in individuals performed stretching exercises.

After eight weeks of training, a nonparametric analysis revealed that the SLR score was significantly improved in the ECC, SS, DS, and SS + ECC groups (all $p < 0.05$) (Figure 2a), although no group effect was noted. This improvement in the SLR test was still evident after the three-month follow-up in the SS, DS, and SS + ECC groups (all $p < 0.05$), with a less notorious improvement observed in the ECC group compared with the DS and SS + ECC groups ($p < 0.05$). Moreover, the SS + ECC group exhibited a significantly greater SLR angle at both the 8-week and 3-month follow-up, compared to the CON group ($p < 0.05$), in the study arm analysis.

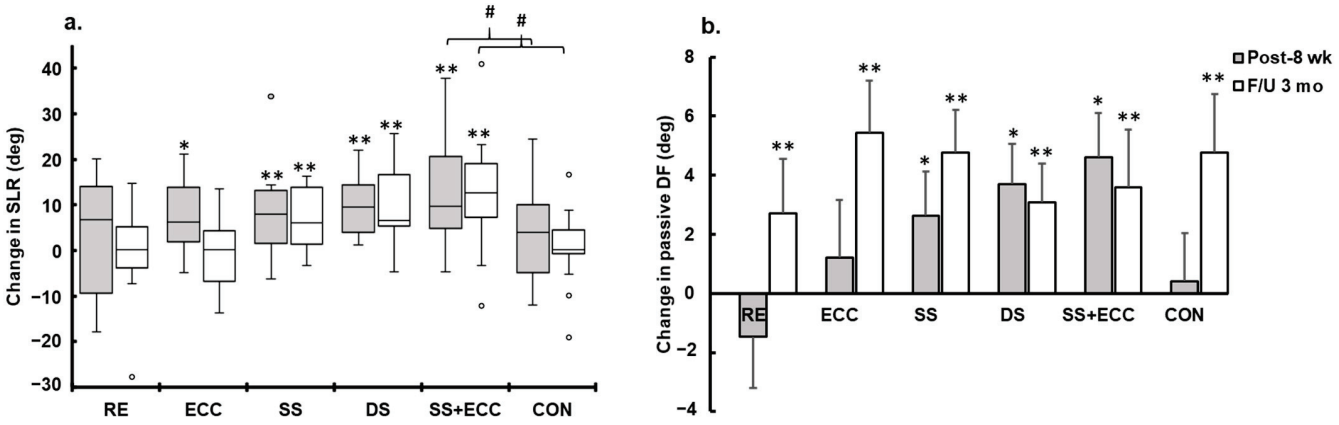


Figure 2. Absolute changes in hamstring (**a**) and calf (**b**) flexibility after eight weeks of home-based interventions and at three-month follow-up. Gray bar, post-eight weeks compared with baseline; blanked bar, three-month follow-up compared with pre-eight-week intervention. Data are presented as median differences and IQR for passive straight-leg raise (SLR), and as mean differences and SEM for passive ankle dorsiflexion (DF) (n = 15). * $p < 0.05$, ** $p < 0.01$. # Significant difference between interventions.

No interaction or group effects were observed for calf flexibility measured during the PDF test. However, a significant time effect was found [$F(2,168) = 21.5$, $p < 0.001$, $\eta_p^2 = 0.20$]. The PDF angle increased in all groups following the eight-week intervention and at the three-month follow-up (Figure 2b). The analysis of each study arm revealed no interaction or group effects for calf flexibility measured during the PDF test. However, a significant time effect was observed in individuals with possible sarcopenia [$F(2,56) = 9.3$, $p < 0.001$, $\eta_p^2 = 0.25$], in those with hamstring tightness [$F(2,56) = 10.2$, $p < 0.001$, $\eta_p^2 = 0.27$], and in individuals with both weaknesses [$F(2,56) = 3.4$, $p = 0.003$, $\eta_p^2 = 0.19$].

A group effect was observed for the knee flexor MTU stiffness [$F(5,84) = 21.5$, $p < 0.001$, $\eta_p^2 = 0.26$], as shown in the baseline comparisons, independent of time or interaction effects ($p > 0.05$) (Figure 3a). There were no significant time, interaction, or group effects for knee flexor MTU stiffness across the three arms in this study (Figure 3a).

A nonparametric analysis revealed an absence of significant changes in PF MTU stiffness after the eight weeks of training across all study arms, with no differences observed between them. However, a decrease in PF MTU stiffness was later observed (at the three-month follow-up) in the RE group, from 0.69 to 0.57 N m/deg ($p = 0.013$), and in the ECC group, from 0.68 to 0.51 N m/deg ($p = 0.035$), independent of group difference (Figure 3b).

Finally, there were no significant differences among the groups in terms of satisfaction with the assigned exercise program, with average satisfaction scores of 2.6, 2.5, 2.4, 2.5, and 2.6 for the RE, ECC, SS, DS, and SS + ECC groups, respectively.

3.3. Physical Activity Volume and Continuous Exercise Sessions During Three-Month Follow-Up

After the three-month follow-up, the overall physical activity in the DS intervention group increased to 150 min per week ($p = 0.049$), whereas for the remaining intervention groups, it remained similar throughout the observation period. The number of continuous exercise sessions during the 3-month follow-up period after the eight weeks of intervention averaged 12, 13, 29, 18, and 20 sessions for the RE, ECC, SS, DS, and SS + ECC groups, respectively. Notably, the exercise frequency in the SS group was significantly higher than that in the RE group ($p = 0.044$).

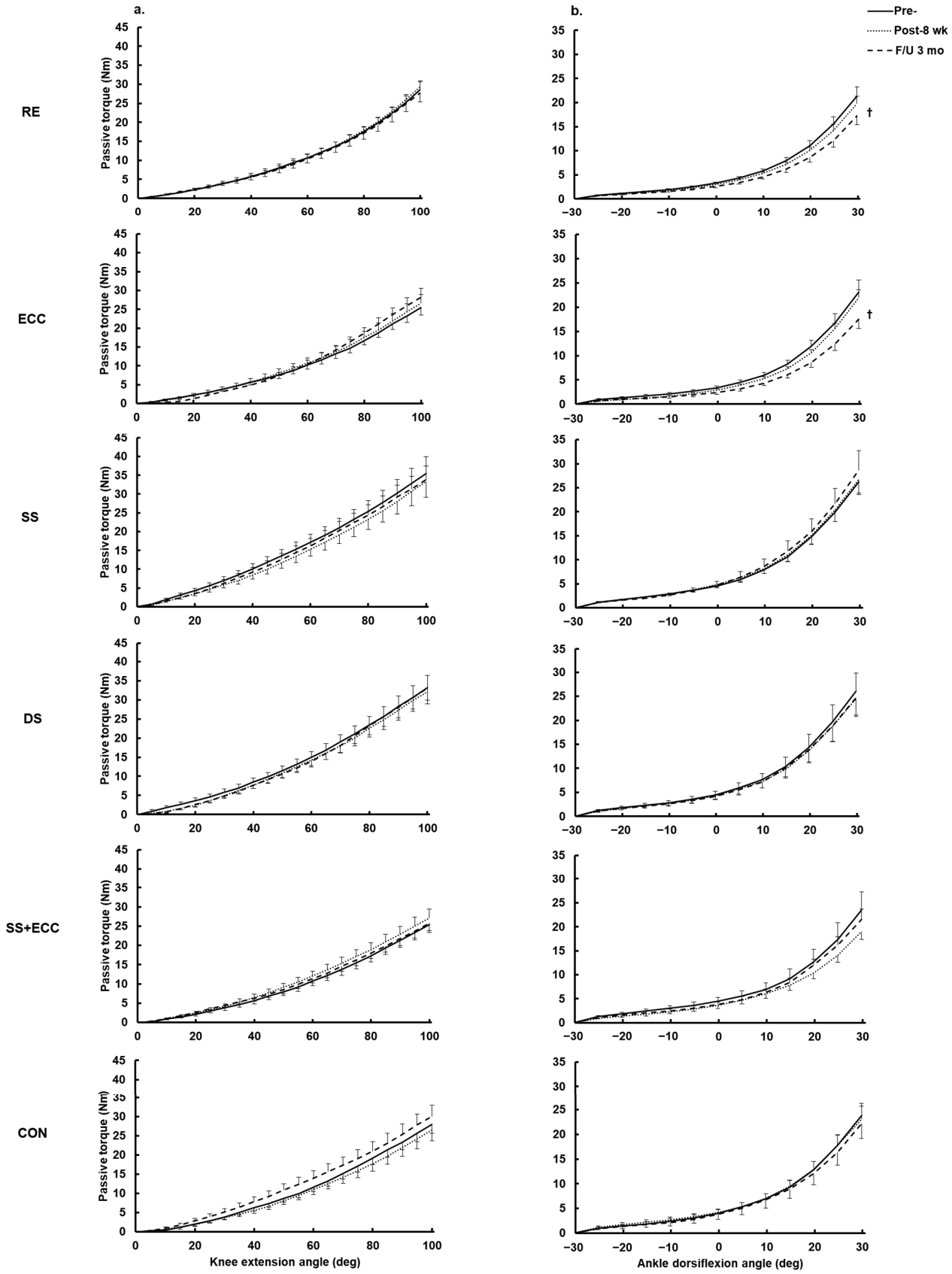


Figure 3. Passive torque–angle relationship of knee flexor (**a**) and ankle plantar flexor (**b**) MTU after eight weeks of home-based interventions and at three-month follow-up. Data are mean and SEM (n = 15). † Significant difference between pre-eight-week intervention and three-month follow-up.

4. Discussion

Aging is associated with the deterioration of various aspects of bodily function, and numerous studies have highlighted the benefits of muscle strengthening and stretching exercises in this context. In this study of older adult participants, special attention was given to addressing individual weaknesses. Home training programs were tailored to target elimination of deficiencies in strength, flexibility, or both. Unexpectedly, no significant differences were found between groups for mobility (TUG) and strength improvement, while it is noteworthy that improvements in mobility and leg strength did not occur simultaneously. The enhancement of leg flexibility was also random, with minor changes observed after the initial eight-week training period, followed by a more pronounced increase at the three-month follow-up. Overall, these improvements seem to be attributable to repeated measurement (learning effect) and/or the increased physical activity of participants, rather than being a direct effect of the home-based training.

The findings in present study partly contrast with previous research linking mobility improvements to strength training over 8–12 weeks [39,40]. Strength training did not provide a greater improvement in mobility upon re-testing compared to other groups. Moreover, the leg isometric strength improved in all groups over time, whereas muscle hypertrophy was observed exclusively in the RE and ECC groups after eight weeks of training, and disappeared within the follow-up period. These discrepancies might be explained by the relatively fit nature of our study population, as the participants were elderly, but otherwise healthy. Despite the inclusion of community-dwelling older adults with possible sarcopenia, as defined by the AWGS 2019 guidelines, the average TUG scores in all groups were above the normative values reported in a recent Thai study [41]. The TUG test is commonly used as a clinical assessment tool for functional performance, and it is widely utilized among older adults [42–44]. It appears that in fit elderly individuals, the TUG test is more sensitive to repeated measures than to strength gains. Therefore, the application of this program to individuals with lower performance levels requires further investigation.

Regarding flexibility changes resulting from the eight-week home-based programs applied in this study, the ECC, SS, DS, and SS + ECC interventions effectively improved hamstring flexibility, which is consistent with previous research [19,22,45,46]. Similar improvements in the PDF angle were observed in the SS, DS, and SS + ECC groups after the intervention. The flexibility improvement may be associated with increased physical mobility, as suggested by previous studies [20–22,47]. However, changes in flexibility and mobility did not always coincide, as no change in mobility was observed after static stretching, despite a significant increase in range of motion.

Unexpectedly, a further increase in the PDF angle was observed during the follow-up period. This could be attributed to continued physical activity or exercise (especially in the DS and SS groups), which contributed further to ROM gains. However, the improvement in leg flexibility in the two pure stretching groups did not differ significantly from that of the other groups during the follow-up period, and inconsistent changes in FL and no changes in MTU stiffness were observed. These results suggest that increased ROM is likely due to enhanced stretch tolerance induced by repeated measures, rather than to the home-based training itself. An increase in leg flexibility without corresponding changes in MTU stiffness highlights the importance of factors beyond passive MTU properties, such as muscle, deep fascia, or nerve tissue stiffness, in overall joint flexibility [17,48].

This study had several limitations. First, the unequal gender distribution across groups may have slightly influenced absolute values. Second, only one side of the body was assessed, leaving contralateral effects unexplored. Third, improvements in physical

function may have involved muscle groups that were not specifically targeted, such as the gluteal muscles. A broader training approach may be necessary to fully assess the impact on overall physical function. Finally, baseline strength and flexibility performance influenced intervention allocation, making it difficult to separate the effects of initial fitness levels from those of the interventions. Nevertheless, we argue that this is not a critical issue, because one would generally expect the occurrence of an adaptation in response to any training program when dealing with training-naïve participants.

Clinical implications

The present study indicates that while most home-based exercise regimens improve functional performance, as shown in previous research [23,24], their benefits generally do not surpass those observed in non-exercised groups. However, strength-based programs demonstrate some superiority by inducing knee extensor muscle hypertrophy. Therefore, both elastic band or eccentric strength training may be recommended for older adults with suspected sarcopenia. Although delayed-onset muscle soreness (DOMS) is a common response to eccentric strength training, it typically occurs within the first few days or weeks of training, with subsequent bouts leading to reduced soreness over time [49].

5. Conclusions

Although increases in physical mobility, strength, and flexibility were observed after targeting muscle weakness or tightness with home-based programs, these improvements appeared to result from learning effects and increased physical activity, rather than the specific impact of the structured training. Strength-based programs, however, provided additional benefits, including short-lasting muscle hypertrophy in knee extensors. Therefore, both elastic band and eccentric strength training may be recommended for older adults with suspected sarcopenia.

Author Contributions: Conceptualization, P.M. and S.K.; methodology, T.V.; software, O.B.; validation, O.B., P.P. and P.C.; formal analysis, P.M. and J.N.; investigation, W.S.; resources, N.L.; data curation, S.C.; writing—original draft preparation, P.M., O.B. and P.C.; writing—review and editing, P.M., O.B., P.C., S.K. and T.V.; visualization, T.V.; supervision, S.K.; project administration, P.M.; funding acquisition, P.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Research Council of Thailand (NRCT) under contract number N42A660935.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Institutional Review Board of Burapha University (IRB1-076/2566, approved 20 July 2023).

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

Data Availability Statement: Data are available upon request.

Acknowledgments: We extend our sincere gratitude to all participants, as well as to Thanakorn Wiriyarattanaporn, Pantita Teerawarodom, Natchaya Tupprapai, and Thidarat Sukhok, for their invaluable support of this project.

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

Abbreviations

The following abbreviations are used in this manuscript:

BF	Biceps femoris
DS	Dynamic stretching
ECC	Eccentric exercise
EI	Echo intensity
FL	Fascicle length
MIVC	Maximum isometric voluntary contraction
MG	Medial gastrocnemius
MT	Muscle thickness
MTU	Musculotendinous unit
PDF	Passive ankle dorsiflexion
RE	Home-based resistance-band exercise
ROM	Range of motion
RPE	Rate of Perceived Exertion
SLR	Straight-leg raise
SS	Static stretching
TUG	Timed Up-and-Go
VL	Vastus lateralis

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Comparative Effects of Resistance Training Modalities on Mental Health and Quality of Life in Individuals with Spinal Cord Injury

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Abstract: Background: Anxiety and depression are prevalent after spinal cord injury, impairing social participation and quality of life. Objective: This study aimed to investigate the effects of traditional resistance training (TRT), flywheel resistance training (FWRT), and high-velocity resistance training (HVRT) on the mental health and quality of life in individuals with spinal cord injury. Methods: Thirty-two participants were divided into TRT (n = 12), FWRT (n = 8), and HVRT (n = 12) groups, undergoing 8 weeks of upper-limb training twice weekly under super-vision. Training intensity and volume were progressively increased. The Hospital Anxiety and Depression Scale and SF-36 Questionnaire were used to assess outcomes. Results: Both the TRT and FWRT groups showed a reduction in HADS-D scores post-intervention ($p < 0.001$). The TRT group also presented a significant reduction in HADS-A scores post-intervention ($p = 0.003$). Concerning quality of life, after training, TRT showed improvements in social functioning ($p = 0.013$), FWRT improved scores in physical functioning ($p = 0.002$), bodily pain ($p = 0.002$), vitality ($p = 0.046$), and role emotional ($p < 0.001$), while HVRT enhanced role physical ($p < 0.001$), social functioning ($p = 0.013$), and role emotional ($p < 0.001$). Conclusion: Overall, TRT was the most effective in reducing anxiety and depression and enhancing quality of life, while FWRT showed notable gains in physical and functional capacity. HVRT demonstrated improvements primarily in role physical but was less effective in other domains.

Keywords: functional capacity; paraplegia; eccentric resistance training; power training; quality of life

1. Introduction

Spinal cord injury profoundly affects multiple aspects of health, directly impacting the quality of life of those affected [1–3]. Spinal cord injury is associated with a range of acute and chronic impairments, including pain, motor dysfunction, sensory deficits, muscle dystonia, fatigue, atrophy, and alterations in muscle fiber composition. These physical

changes often lead to reduced strength, deteriorated body composition, and gradual declines in both functionality and independence, highlighting the extensive long-term challenges faced by individuals with spinal cord injury [4–6]. In a recent study, Lee et al. [7] found that functionality losses were associated with psychological issues like anxiety, depression, sleep disorders, and suicide risk. Functional deficits also influence community participation and employment, which also might lead to mental health disorders [8–10].

Evidence suggests that, compared with able-bodied individuals, people with spinal cord injury are more likely to experience anxiety and depression. Approximately 22% of people with spinal cord injury are estimated to experience anxiety, while depression affects around 30% of this population [10]. Furthermore, the research shows that anxiety and depression can affect both paraplegic and tetraplegic individuals similarly, with injury severity or physical limitations not being the primary factors in the development of psychological disorders after spinal cord injury [11,12].

Physical exercise plays a valuable role in recovery strategies and treatments aimed at improving functionality and independence in daily activities, fostering autonomy, and preventing secondary complications. Resistance training stands out as an effective and reliable approach that not only enhances body composition and strength but also has positive effects on the mental health of individuals with spinal cord injury [4,13–15]. Additionally, active exercise induces both peripheral and central effects, promoting neuroplasticity, the release of brain-derived neurotrophic factors, pain modulation, and the normalization of GABA–glutamate neurotransmission, which are mechanisms associated with improvements in physical and mental health [16,17]. These effects highlight the potential of exercise to address both functional and psychological challenges in individuals with spinal cord injury.

Among resistance training methods, two are particularly beneficial for individuals with spinal cord injury: flywheel resistance training (FWRT) and high-velocity resistance training (HVRT). FWRT offers unique advantages by combining eccentric overload with concentric actions, leading to improved strength and power output with lower energy demands. This method also supports high-threshold motor unit recruitment and contributes to increases in muscle mass, fascicle length, and tendon strength [18–20]. This aligns with the findings of Stone et al. [21], who demonstrated that eccentric resistance training in individuals with incomplete spinal cord injuries, performed twice weekly over 12 weeks, was effective in improving both eccentric and isometric strength.

Equally, HVRT has shown significant improvements in functional capacity, muscle strength, and power, with these benefits achieved through low-to-moderate training loads—an important advantage for individuals with spinal cord injury-related limitations [22,23]. Recently, a study conducted by Rodrigues et al. [14] demonstrated that high-intensity resistance training with progressive volume, performed twice weekly over 12 weeks, can improve or maintain body composition, enhance upper limb muscle power, anaerobic power, and explosive strength. These improvements positively impact functional capacity, promoting greater autonomy and reflecting improvements in the mental state and quality of life for individuals with spinal cord injury. These results highlight the potential of FWRT and HVRT as effective and accessible training methods for individuals with spinal cord injury, targeting both strength and functionality with notable efficiency. However, the impacts of resistance training modalities may vary based on the severity of spinal cord injuries and individual specific factors.

Although the benefits of FWRT and HVRT are well documented compared with traditional resistance training (TRT) or other forms of RT, a knowledge gap remains regarding their specific effects on individuals with spinal cord injury. Therefore, this study aims to compare the effects of TRT, FWRT, and HVRT on mental health (anxiety and depres-

sion) and quality of life. We hypothesize that all three training modalities will lead to improvements in the mental health and quality of life in individuals with spinal cord injury.

2. Materials and Methods

2.1. Experimental Approach to the Problem

This experiment aimed to compare the effects of TRT, FWRT, and HVRT on mental health and quality of life outcomes in people with spinal cord injury. Given TRT's established effectiveness in this population, it was used as a control group to encourage participant engagement and facilitate attendance during initial and final evaluations. This approach also addressed the unique mobility and adherence challenges faced by the spinal cord injury population. Training protocols followed principles designed to sustain intensity and gradually increase training volume, optimizing the training load throughout this study. Participants were fully briefed on this study's procedures, with opportunities provided to address questions individually or in group settings.

2.2. Subjects

The sample consisted of 34 individuals familiar with the university's programs for people with disabilities, alongside additional participants recruited through a partnership with the city hall. Inclusion criteria required a clinically confirmed spinal cord injury, no upper limb musculoskeletal injuries within the past year, no prior RT experience, and a commitment to attend at least 80% of sessions without beginning other exercise programs. Participants were also asked to maintain their regular diets. Participants' ages ranged from 28 to 65 years (49 ± 11.78), with time since injury averaging 22 ± 17.32 years, and an average weight of 64.62 ± 3.33 kg (Figure 1).

Throughout this study's conception, potential inclusion and exclusion criteria and their possible impacts on the results were widely discussed. However, it is well known that individuals with spinal cord injury may develop various secondary effects, such as hypertension, anxiety, and depression. Additionally, these individuals face significant mobility challenges, which represent a major exclusion factor. For this reason, it was decided that only musculoskeletal injuries in the upper limbs would constitute grounds for volunteer exclusion.

Spinal cord injuries are highly unpredictable, as two similar injuries can lead to distinct sequelae, such as muscle rigidity or flaccidity. Considering these characteristics, the lead researcher responsible for the initial contact with the volunteers conducted an interview to better understand each individual's potential and limitations. After all interviews were completed, it was determined that grouping participants based on injury level would be sufficient to minimize biases in the results.

During the initial contact between the volunteers and the researcher responsible for group allocation, a brief interview was conducted, during which the informed consent form was presented, and any questions regarding the assessments, training period, and other relevant details were clarified.

At this stage, the researcher collected documents confirming the spinal cord injury and discussed each volunteer's limitations and potential abilities. All participants had complete injuries resulting from firearm wounds or automobile accidents. Furthermore, the researcher observed that the volunteers had traumatic spinal cord injuries at different levels, with lesion sites ranging from T4 to L1 vertebrae.

Given the diversity in participants' physical conditions, randomization was not applied. Instead, the principal researcher assigned participants to groups to ensure homogeneity in terms of injury type and level, along with functional potential and limitations.

This grouping method avoided clustering similar injuries in one group, which might have skewed the results. The researcher responsible for group assignments did not participate in data collection or training sessions, contributing only to statistical analysis and interpretation of results. This research was previously approved by the Ethics Committee of the Federal University of Viçosa under the number 5.418.335 in May of 2022 and performed during the second semester of 2023.

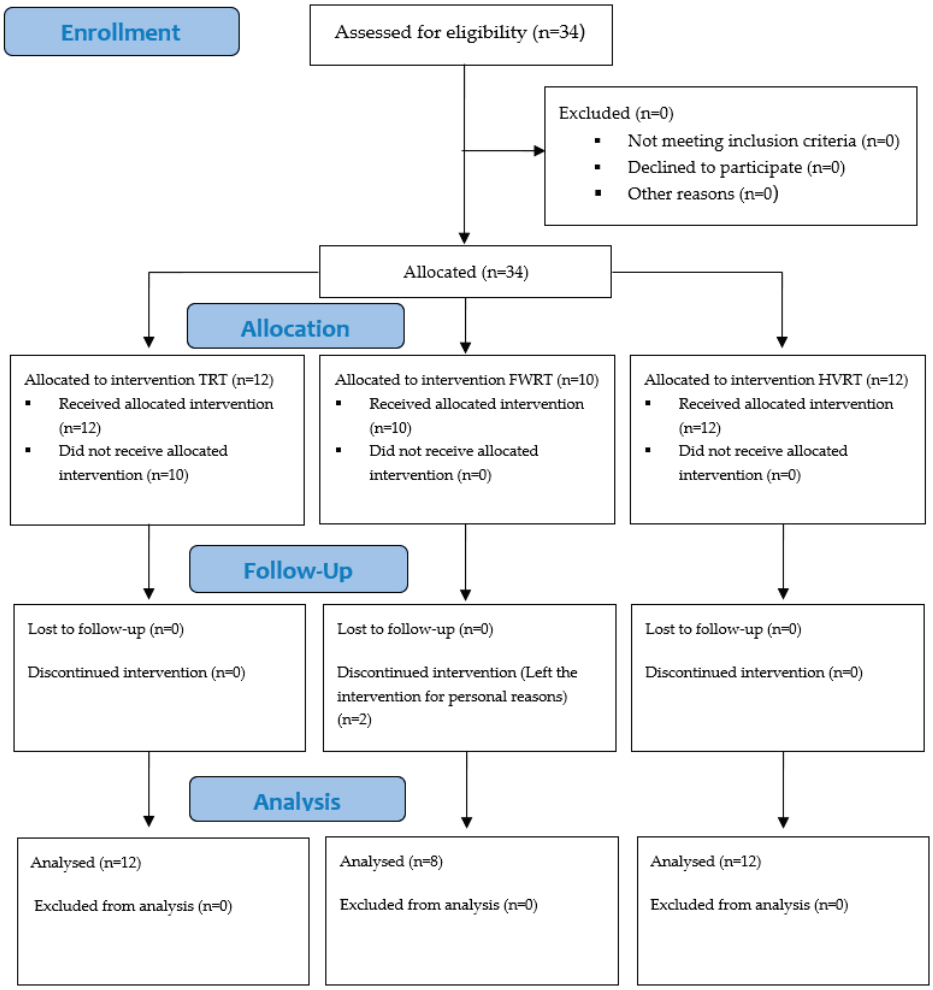


Figure 1. Study trial design. Overview of volunteer group allocation and dropout information. Flywheel resistance training (FWRT), high-velocity resistance training (HVRT), traditional resistance training (TRT).

2.3. Procedures

2.3.1. Training Protocols

Thirty-four participants were divided into three groups: TRT (n = 12), FWRT (n = 10), and HVRT (n = 12). In the FWRT and HVRT groups, the focus was on executing the concentric phase of each movement as quickly as possible. FWRT participants followed the machine's motion during the eccentric phase and braked in the last third to maximize eccentric overload benefits from the inertial flywheel machine (multi-leg isoinertial, Physical Solutions, São Paulo, Brazil). HVRT participants performed the eccentric phase in a controlled manner, not exceeding 2 s. TRT participants maintained a 2 s duration for both concentric and eccentric phases. The training period lasted eight weeks, with two sessions per week, progressively increasing in duration from 25 to 50 min from the first to the last week. Each session included two warm-up sets with a light load (50% of the

training load). The training volume ranged from 2 sets of 8 repetitions to 4 sets of 12 (see Figure 2), and the training sessions focused on exercises for the functional upper body muscles and specific individual needs. Individual adjustments varied from researcher assistance in securing the wheelchair in the appropriate position to the use of bars with different diameters to facilitate grip during exercise execution and straps to stabilize the participant's torso against the wheelchair backrest. Accordingly, all three groups performed exercises targeting the back, pectoralis major, deltoids, biceps, triceps, forearms, and core muscles. All participants performed the same exercises in the same sequence, with minor adjustments to enhance their safety and comfort. Training intensity was monitored using the OMNI-RES scale (1 to 10), with perceived exertion maintained between 7 and 9, and a 1 min rest was allowed between sets. All sessions and evaluations took place in the Department of Physical Education at the Federal University of Viçosa.



Figure 2. Description of the exercises performed by each group and weekly training volume throughout the intervention.

2.3.2. Mental Health and Quality of Life Assessment

For the assessment of mental health and quality of life, two questionnaires were administered. The Hospital Anxiety and Depression Scale (HADS) was used specifically to measure symptoms of anxiety and depression, in its Brazilian validated version [24]. This scale includes 14 multiple-choice items divided into 2 subscales, 1 for anxiety and 1 for depression, each containing 7 items scored from 0 to 3. The total score for each subscale ranges from 0 to 21, with a cutoff score of $\geq$8 indicating possible anxiety or depression. Designed for use in non-psychiatric settings, HADS is a brief user-friendly tool, allowing patients to respond based on their experiences over the previous week. In addition to HADS, the SF-36 questionnaire was administered to evaluate quality of life across eight domains. This instrument is based on a thorough review of previous tools and is designed to capture changes in health, functional limitations, and social factors. Scores on SF-36 range from 0 to 100, with higher scores indicating a better quality of life [25]. Together, HADS and SF-36 provide a comprehensive assessment of mental health and quality of life, reflecting both emotional well-being and functional status.

2.4. Statistics

For the statistical analysis, descriptive statistics were initially applied to summarize the data. The Shapiro–Wilk test assessed data normality, and for variables that did not meet the normality assumption, a log transformation (base 10) was applied to normalize the data, allowing for the consistent use of parametric tests across all analyses. Box's M test was used to evaluate the homogeneity of variances. Group comparisons at baseline were conducted with a one-way analysis of variance (ANOVA), followed by Bonferroni post hoc analysis. To examine intra- and intergroup differences over time, a two-way repeated measures ANOVA was used, incorporating two factors: time (pre- and post-intervention) and condition (comparing TRT, FWRT, and HVRT groups). A significance level of $p < 0.05$ was established for all tests. Analyses were performed using SPSS software, version 21.0.

3. Results

3.1. Mental Health

The TRT and FWRT groups showed a reduction in HADS-D (Figure 3A) values at the post-intervention time point compared with the pre-intervention time point ($p < 0.001$; $\eta^2 = 0.776$; $\beta = 1.00$). Specifically, the TRT group also exhibited a reduction in HADS-A (Figure 3B) values at the post-intervention time point compared with the pre-intervention time point ($p = 0.003$; $\eta^2 = 0.517$; $\beta = 0.931$). Furthermore, in the comparison between groups at the post-intervention time point, it was observed that the TRT group had lower HADS-A values compared with the FWRT and HVRT groups ($p < 0.001$; $\eta^2 = 0.720$; $\beta = 0.995$), indicating a moderate to large effect.

3.2. Quality of Life

Figure 2 presents quality of life data, with results indicating changes across various assessed domains. In the domain of physical functioning (Figure 4A), the FWRT group showed higher values after the intervention compared with the pre-intervention time point ($p = 0.002$; $\eta^2 = 0.500$; $\beta = 0.951$), although no differences were observed between groups at the post-intervention time point ($p = 0.306$; $\eta^2 = 0.155$; $\beta = 0.234$). For role physical (Figure 4B), the FWRT group showed higher values after the intervention ($p < 0.001$; $\eta^2 = 0.721$; $\beta = 1.00$) and also compared with the TRT and FWRT groups ($p < 0.001$; $\eta^2 = 0.893$; $\beta = 1.00$). In the bodily pain domain (Figure 4C), the FWRT group showed higher values, while the HVRT group showed lower values after the intervention

($p = 0.002$; $\eta^2 = 0.500$; $\beta = 0.951$). Additionally, the FWRT group presented higher values at the post-intervention time point compared with the HVRT group ($p = 0.001$; $\eta^2 = 0.622$; $\beta = 0.977$).

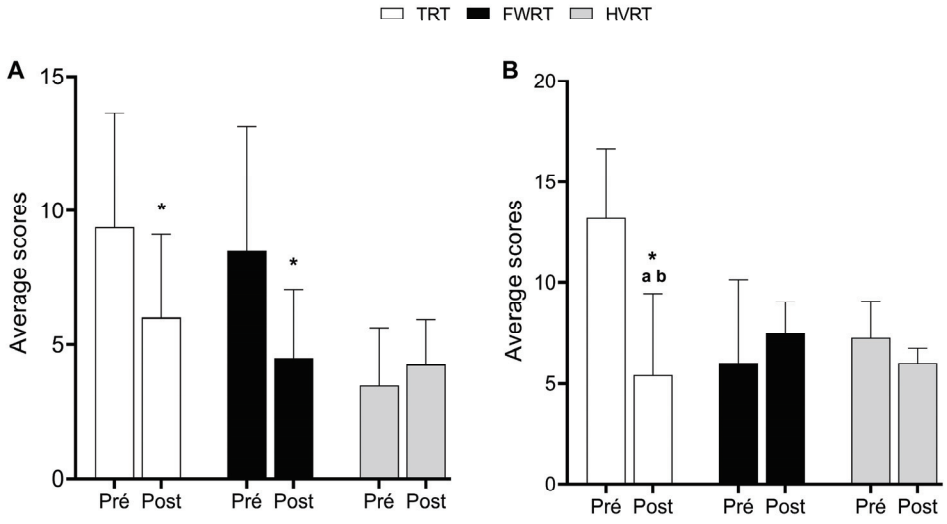


Figure 3. Hospital Anxiety and Depression Scale (HADS). (**A**) Depression (HADS-D). (**B**) Anxiety (HADS-A). Data are presented as means ± standard deviation. * $p < 0.05$ vs. post intervention; [a] $p < 0.05$ vs. FWRT; [b] $p < 0.05$ vs. HVRT. Two-way repeated measures ANOVA followed by Bonferroni post hoc analysis.

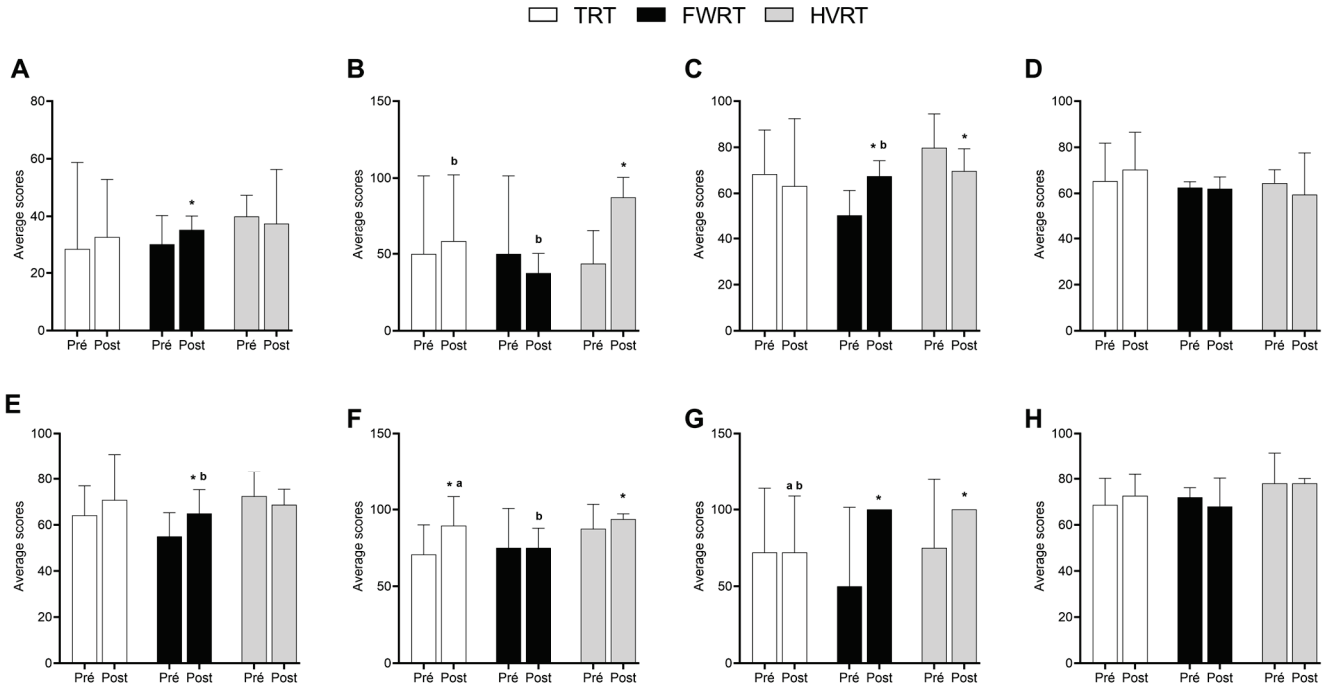


Figure 4. SF-36 health questionnaire. (**A**) Physical functioning; (**B**) role physical; (**C**) bodily pain; (**D**) general health; (**E**) vitality; (**F**) social functioning; (**G**) role emotional; (**H**) mental health. Data are presented as means ± standard deviation. * $p < 0.05$ vs. post-intervention; [a] $p < 0.05$ vs. FWRT; [b] $p < 0.05$ vs. HVRT. Two-way repeated measures ANOVA followed by Bonferroni post hoc analysis.

For general health (Figure 4D), no changes were observed over time or between groups ($p = 0.958$; $\eta^2 = 0.000$; $\beta = 0.050$ and $p = 0.248$; $\eta^2 = 0.180$; $\beta = 0.273$, respectively). In the vitality domain (Figure 4E), the FWRT group showed higher values after the intervention

compared with the pre-intervention time point (p = 0.046; η^2 = 0.240; β = 0.530) and lower values compared with the HVRT group (p = 0.047; η^2 = 0.355; β = 0.598). For social functioning (Figure 4F), the TRT and HVRT groups showed higher values after the intervention (p = 0.013; η^2 = 0.347; β = 0.752). Between groups, the FWRT group showed lower values compared with the TRT and HVRT groups (p = 0.008; η^2 = 0.501; β = 0.861).

In the role emotional domain (Figure 4G), the FWRT and HVRT groups showed higher values after the intervention ($p < 0.001$; η^2 = 0.582; β = 0.989). Additionally, the TRT group showed lower values at the post-intervention time point compared with the FWRT and HVRT groups (p = 0.004; η^2 = 0.427; β = 0.877). Finally, in the mental health domain (Figure 4H), no changes were observed over time or between groups (p = 0.979; η^2 = 0.000; β = 0.050 and p = 0.138; η^2 = 0.124; β = 0.400, respectively).

No adverse effects related to the training were reported by the volunteers, regardless of the training group. This supports evidence indicating the safety and feasibility of the resistance training methods used in this study.

4. Discussion

This study investigated the effects of three RT protocols—TRT, FWRT, and HVRT—on the mental health and quality of life in people with spinal cord injury. The results demonstrated distinct benefits among the groups, indicating that different approaches may offer specific advantages in managing these outcomes, depending on the characteristics and needs of the individuals.

4.1. Mental Health

Initially, the TRT and FWRT groups showed a reduction in HADS-D values after the intervention, corroborating the literature that highlights the ability of RT interventions to mitigate symptoms of depression in populations with adverse health conditions [26–28]. Specifically, TRT also demonstrated a significant reduction in HADS-A values, results that are particularly relevant since depression and anxiety are often associated with a decreased quality of life and limitations in the social reintegration of people with spinal cord injury [29–31].

The intergroup analysis revealed that TRT was more effective in reducing HADS-A compared with the FWRT and HVRT groups, indicating a relevant effect. This advantage may be related to the simplicity and predictability of the TRT protocol, which creates a more comfortable and safer environment for practice, reducing stress levels associated with exercise. These findings reinforce the relevance of interventions that combine regular physical stimuli adjusted to individual capacities, especially in populations facing emotional and physical challenges due to the complexity of their conditions [32,33].

4.2. Quality of Life

Regarding quality of life, the results demonstrated specific benefits for each training protocol. TRT showed a significant increase in social functioning, highlighting its contribution to improving the social interaction of people with spinal cord injury. This type of training is recognized for fostering social interaction due to its structured environment and the encouragement of participation in group activities [34–36]. These same mechanisms may have contributed to the observed results in this population, promoting greater social engagement and support during the sessions.

Additionally, the FWRT group showed improvements in physical functioning, bodily pain, vitality, and role emotional, demonstrating its ability to promote enhancements in physical functionality, energy levels, and confidence in managing emotional limitations.

Previous studies have already reported significant improvements in physical functionality and pain perception using this training method [14,37,38]. Therefore, this improvement in functional capacity may have contributed to the observed advancements in other domains by providing greater autonomy and facilitating the execution of daily tasks.

Furthermore, the HVRT group demonstrated improvements after the training period in the domains of role physical, role emotional, and social functioning, highlighting its positive impact on these aspects. These improvements may be related to the intense stimulus of the protocol, known for promoting gains in muscle functionality and quality of life by reducing perceived limitations in social and emotional interactions [39,40]. However, the significant increase in bodily pain may reflect the high physical effort required, emphasizing the importance of adjustments in intensity and progression to minimize discomfort and maximize benefits.

Building on these findings, although certain domains, such as general health, did not show significant changes, maintaining these aspects is already a positive outcome, considering the challenges faced by people with spinal cord injury. The varied impact of the protocols underscores the need for individualized interventions, integrating different training modalities to maximize benefits across multiple domains of quality of life.

Rivers et al. [41] identified a positive association between higher motor function (assessed by the functional independence measure (FIM)) and quality of life in the physical domain of SF-36V2, whereas a negative association was observed in the mental domain. While a lower FIM motor score reflects greater injury severity and poorer physical health, its correlation with higher self-reported mental health is less intuitive. Furthermore, Ditor et al. [42] demonstrated that adherence to exercise enhances quality of life, with significant benefits observed following a 9-month training intervention and an additional 3-month follow-up, including reductions in stress and pain, along with the promotion of an active lifestyle in individuals with spinal cord injury.

In the comparison between the groups, specific differences emerged in the evaluated domains. For instance, the HVRT group showed the best results in role physical and vitality, demonstrating its effectiveness in promoting functional and energetic gains. The FWRT group performed better in bodily pain, suggesting its potential for managing physical discomfort. In the domain of social functioning, TRT and HVRT outperformed FWRT, highlighting their ability to foster social interactions. In role emotional, FWRT and HVRT showed higher values compared with TRT, reinforcing their applicability in reducing emotional limitations. These findings suggest that each protocol can be tailored to specific needs, enabling personalized approaches.

4.3. Limitations and Strengths of This Study

This study presents some limitations stemming from the challenges of assembling a homogeneous group of people with spinal cord injury and related conditions, including factors such as varying times since injury, differences in trunk stability, and upper limb mobility levels. For this reason, participants were allocated to groups based on the assessment of an experienced researcher, aiming to balance the limitations and strengths present in a heterogeneous group. There was only one flywheel machine available in the laboratory where the FWRT was conducted, which limited interaction among volunteers during training sessions. This may have affected participants' motivation throughout the training program.

Furthermore, the findings related to FWRT should not be associated with other types of eccentric training, as they represent distinct stimuli and should only be compared under equivalent conditions. It is also important to highlight the limitation in comparing TRT

and FWRT, as there is no direct equivalence in execution speed and repetition duration. Therefore, being mindful of this, volunteers in the FWRT and HVRT groups were instructed and encouraged to perform the concentric phases at the highest possible speed, ensuring that all repetitions were executed at maximum or near-maximum intensity.

On the other hand, several strengths should be highlighted. Validated and widely recognized tools were chosen to assess mental health and quality of life. Furthermore, it is noteworthy that this is the first study to apply three different types of RT with similar training protocols in people with spinal cord injury, enabling a comparison between them. The present study also appears to be the first to use a flywheel machine and HVRT with this population. We hope this will encourage other researchers to further explore these methods and expand the range of training modalities available for individuals with spinal cord injury. Long-term studies spanning several months or years, along with follow-ups after training cessation, could be highly valuable for a deeper understanding of the findings presented in this study.

Despite its limitations, this study's strengths help mitigate its impact and underscore its contributions. The heterogeneity in participant characteristics was addressed through careful group allocation, ensuring a balanced distribution of strengths and limitations. While limited flywheel equipment may have restricted interaction, this study's pioneering use of flywheel resistance training in individuals with spinal cord injury paves the way for future research. Differences in execution speed and repetition duration between traditional resistance training and flywheel resistance training were managed by standardizing volume.

4.4. Practical Applications

The results of this study highlight the importance of integrating different resistance training modalities (TRT, FWRT, and HVRT) into rehabilitation programs for individuals with spinal cord injury, considering the rapid and effective potential of these interventions. Each modality demonstrated specific benefits that can be explored according to individual needs. TRT proved effective in reducing symptoms of anxiety and improving social interaction, making it an ideal option to promote greater social engagement in controlled environments. On the other hand, FWRT stood out for improving physical functionality and reducing pain perception, offering an efficient alternative for muscle recovery and the performance of daily activities. Meanwhile, HVRT presented significant benefits in vitality and overcoming emotional limitations, contributing to greater autonomy and confidence.

Furthermore, one of the main practical applications is the rapid positive impact provided by these modalities. Even with a short intervention period of just eight weeks, with two weekly sessions, significant improvements were observed. This effect can be enhanced with increased training frequency or prolonged practice periods, highlighting resistance training as an effective and accessible approach for this population. Thus, a personalized strategy, combining modalities and adapting the frequency and duration of training, can maximize the physical and psychological benefits for people with spinal cord injuries, promoting their rehabilitation and quality of life.

Beyond the physical improvements, the observed benefits extend to important psychopathological outcomes, such as reduced anxiety, enhanced vitality, and improvements in emotional resilience. These results demonstrate how resistance training contributes to better mood regulation, reduced emotional distress, and increased self-efficacy, creating a feedback loop where physical gains reinforce psychological well-being. The enhanced sense of control and competence may help individuals manage stress more effectively, supporting long-term adherence to rehabilitation programs. Improved social interaction,

facilitated by reduced anxiety and increased physical functionality, can further promote reintegration into daily life and community activities, improving overall quality of life. This highlights resistance training as a multidimensional therapeutic tool that addresses both physical recovery and psychopathological well-being.

5. Conclusions

In our findings, we observed that not only TRT has positive effects but also FWRT and HVRT are training modalities that can be applied to people with spinal cord injury to improve their mental health and quality of life. As demonstrated in the results, each training type led to specific outcomes, which may indicate that varying training modalities could significantly benefit this population. This leads us to understand that individuals with spinal cord injury should engage in resistance training regardless of the specific type employed.

Author Contributions: Conceptualization, L.V.S., E.T.P., C.E.P.d.O. and O.C.M.; methodology, L.V.S., K.R.d.S.R.F., C.E.P.d.O. and O.C.M.; original draft preparation, writing—review and editing, L.V.S., K.R.d.S.R.F., L.B.L., P.F., E.T.P., C.E.P.d.O. and O.C.M.; data curation, L.V.S. and K.R.d.S.R.F.; formal analysis, C.E.P.d.O. and O.C.M.; resources, L.V.S. and O.C.M.; funding acquisition, C.E.P.d.O., E.T.P. and O.C.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Fundação de Amparo à Pesquisa de Minas Gerais (FAPEMIG) under grant APQ-02263-21 and by a scholarship awarded to L.B.L. through the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES)—Finance Code 001.

Institutional Review Board Statement: This study was approved by the Research Ethics Committee involving human beings of the Federal University of Viçosa, Minas Gerais, Brazil, and was conducted under license number CEAP: 51624715.2.0000.5153, approval date: 19 March 2022.

Informed Consent Statement: All subjects participated voluntarily, signed the free and informed consent form and received information about this study, as determined by the Resolution 466/2012 of the National Health Council.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author, (PF), upon reasonable request.

Acknowledgments: Coordination of Improvement of Higher Level Personnel (CAPES).

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

Abbreviations

The following abbreviations are used in this manuscript:

FWRT	Flywheel Resistance Training
HVRT	High-Velocity Resistance Training
TRT	Traditional Resistance Training
HADS	Hospital Anxiety and Depression Scale
HADS-D	HADS Depression Score
HADS-A	HADS Anxiety Score

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Review

Characterization of Load Components in Resistance Training Programs for Kidney Transplant Recipients: A Scoping Review

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Abstract: Resistance training (RT) has been shown to produce beneficial effects, including on quality of life, renal function, physical fitness, and survival rates in kidney transplant for 24 recipients. However, the optimal periodization of load components for this population remains unclear, as no consensus has been established. This study aimed to characterize the load components of RT programs in kidney transplant recipients. A scoping review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR). The literature search was performed up to October 2024 in MEDLINE/PubMed, the Web of Science Core Collection, SCOPUS, ScienceDirect, and SPORTDiscus. Only studies that included RT as part of the intervention were considered. The RT variables analyzed included intervention duration, weekly frequency, session duration, number and types of exercises, intensity, number of sets, rest time between sets, progressive overload, and execution velocity. A total of 645 studies were identified, of which 15 met the eligibility criteria and were selected for analysis. The primary strategy for intensity control was based on the percentage of one-repetition maximum (%1RM), with training zones ranging from 30% to 80%. The number of sets varied from two to eight, while repetitions ranged from 10 to 20. The rest intervals between sets lasted between one and five minutes. The most highly implemented type of resistance involved the use of dumbbells, body weight, and elastic bands. A high degree of heterogeneity was identified in load periodization parameters, highlighting a lack of consensus in exercise prescription for this population. However, this review established general criteria that can serve as a reference for exercise professionals to develop more structured and effective training programs.

Keywords: renal transplantation; kidney grafting; exercise; strength training

1. Introduction

Kidney transplantation is the most effective strategy for treating individuals with end-stage renal disease, providing multiple benefits such as improved quality of life and increased survival rates [1,2]. However, as part of their post-surgical treatment, these patients receive immunosuppressive medications, which weaken the immune system and increase the risk of metabolic disturbances associated with the recurrence of non-communicable diseases [3–5]. Given this issue, it is essential for these individuals to adopt healthy lifestyle habits that counteract the adverse effects of these medications and contribute to better immune system function [6–8]. In this regard, previous research has established that obesity, metabolic syndrome development, physical inactivity, and poor dietary habits are among the risk factors associated with premature mortality, cardiac events, and graft loss [9,10].

One of the most effective strategies for improving specific health outcomes in this population, while simultaneously reducing the risk of metabolic diseases, is the incorporation of physical exercise into their daily routines [11–15]. A recent meta-analysis, including a total of sixteen randomized clinical trials with 827 patients, demonstrated that supervised physical exercise resulted in favorable changes in cardiorespiratory capacity, physical fitness, creatinine levels, quality of life, and high-density lipoprotein cholesterol (HDL-c) values [16]. However, the findings of this study suggest that due to variability in interventions, it is not possible to conclude which exercise modality is the most effective. It was only established that most successful studies proposed a frequency of three sessions per week, with a duration of 30 to 60 min per session, over a period of three to six months. Furthermore, it is suggested that the cardiorespiratory component should be programmed at 60% to 70% of maximum heart rate, while strength training should be performed twice a week [16]. Additionally, a recent clinical practice guideline on lifestyle in renal disease, specifically in transplant recipients, indicates that engaging in physical exercise improves survival rates in these patients [17]. However, regarding load periodization parameters, the guideline only generally mentions the importance of combining resistance and endurance training, without delving into specific components such as intensity, volume, recovery times, density, and execution velocity.

In the last decade, there has been a paradigm shift in how resistance training (RT) is programmed and dosed [18]. In this regard, various studies have aimed to standardize the correct methodology for periodizing all load components [19,20]. RT has been widely used as an intervention strategy for kidney transplant recipients, demonstrating positive effects on health. However, there is considerable heterogeneity in how these exercise programs are prescribed, making it difficult to establish an optimal model for load periodization and progression. Currently, no specific guidelines provide clear recommendations for structuring strength training programs in this population, posing a challenge for exercise professionals. Given the need for evidence-based guidelines to support the programming of strength training for kidney transplant recipients, this exploratory review aims to characterize the load components used in these training programs. By identifying patterns in exercise prescription and detecting gaps in the literature, this study seeks to provide valuable insights that can contribute to the development of more precise recommendations for professional practice.

2. Materials and Methods

2.1. Protocol and Registration

A scoping review was conducted following the reporting Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR) [21]. The review protocol was registered on Open Science Framework https://osf.io/2bh9z/ (accessed on 2 May 2024)-The Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR) checklist is presented in Supplementary Table S1.

2.2. Eligibility Criteria

This review included primary studies with clinical trial designs (randomized or non-randomized controlled studies) that evaluated the effect of RT programs, either supervised or unsupervised on any type of outcomes in kidney transplant recipients. RT programs featuring free weights (i.e., with or without external overload [weights, elastic band]) and machines were considered. Study interventions with other types of methodologies such as endurance training (in treadmill or bicycle and multi-component) were not included in the scope of this review.

2.3. Information Sources

The search for studies was carried out in the following databases: MEDLINE/PubMed, the Web of Science Core Collection, SCOPUS, Science Direct, and SPORTDiscus. The reference lists of the selected articles were also manually searched for additional literature (snowballing).

2.4. Search Strategy

The population, concept, and context (PCC) mnemonic was utilized for structuring our research question [22]: P (kidney transplant recipients), C (RT protocols), and C (detailed RT variables according to the National Strength and Conditioning Association [NSCA] recommendations: training methodology, exercise selection, sets, repetitions, intensity, load progression, rest interval between sets, execution velocity, weekly frequency, and duration of RT intervention [23–25]). The search strategy was composed of the keywords: ("resistance training" OR "resistance exercise" OR "strength training" OR "strength exercise" OR "weight exercise" OR "weight training" OR "exercise training") AND ("kidney transplantation" OR "renal transplantation" OR "kidney transplant recipients" OR "kidney grafting"). The search strategy for each specific base is presented in Supplementary Table S2. The searches were carried out without applying restrictions by year of publications, but only articles written in the English language were included. Before submitting the manuscript, an updated bibliographic search was conducted to incorporate the most recent and relevant studies. As a result of this update, two additional studies were included in the analysis.

2.5. Method for Evidence Source Selection

Two research carried out the searches in the proposed databases and the identified studies were imported into EndNote™ Basic to remove the duplicates. Subsequently, the authors (JP and CL) reviewed the full text to determine the inclusion of the study according to the eligibility criteria. A third reviewer (LC) analyzed disagreements and determined which studies were included in the review.

2.6. Data Charting Process and Items

The selected studies were analyzed independently by each researcher, extracting the following information in an Excel rubric. In studies reporting combined exercises (concurrent training), only the RT information was extracted:

- General information of the study: year of publication, design, sample size, age, sex and post-transplant time of the participants.
- Characteristics of the RT program: training methodology, exercise selection, sets, repetitions, intensity, load progression, rest interval between sets, execution velocity, weekly frequency, and duration.

2.7. Data Extraction and Analysis Process

A qualitative descriptive analysis of the training programs was carried out. The researchers extracted the information presented in each manuscript in the methodology sections. In cases where one of the proposed characteristics was not clearly specified in the text, it was recorded as "not reported". At the end of this process, cross-checking of all the information retrieved was carried out. A third review by an experienced proofreader resolved the divergences.

3. Results

3.1. Selection of Sources of Evidence

Initially, 645 studies were identified. After removing duplicates, 501 titles and abstracts were screened, resulting in 26 potentially eligible full texts. A total of 15 studies were included in this review. Figure 1 presents the PRISMA flow diagram of this study.

3.2. Characteristics of Sources of Evidence

Table 1 shows the characteristics of the selected studies. A total of 666 participants were included across all studies, with both men and women taking part in the 15 interventions [26–40]. The age of the experimental groups ranged from 27 to 56 years. The post-transplant time before initiating the physical exercise program was reported in only five studies with a mean of 57.6 months.

Table 1. General characteristics of the studies.

Author	Research Design	Sample Size	Sex	Age Experimental Group (Years)	Post-Transplant Time (Experimental Group)
Roi et al., 2018 [26]	NRCT	EG:52 CG:47	F/M	47 ± 12	5.1 ± 2.1 (years)
Hernández et al., 2021 [27]	RCT	EG:8 CG:8	F/M	49.7 ± 9.6	115 ± 54 (months)
Hemmati et al., 2022 [28]	RCT	EG:13 CG:10	F/M	32.9 ± 9.81	NR
Michou et al., 2023 [29]	RCT	EG:13 CG:12	F/M	54.9 ± 9.9	NR
Lima et al., 2019 [30]	RCT	EG:7 CG: 15	F/M	54 ± 3	4 ± 1.8 (years)
Michou et al., 2022 [31]	RCT	EG:11 CG:10	F/M	52.9 ± 9.5	47.4 ± 18.3 (months)
Eatemadololama et al., 2017 [32]	NRCT	EG:12 CG:12	NR	27.4 ± 17.3	NR

Table 1. *Cont.*

Author	Research Design	Sample Size	Sex	Age Experimental Group (Years)	Post-Transplant Time (Experimental Group)
Zhang et al., 2023 [33]	RCT	EG:53 CG:53	F/M	43.16 ± 10.76	NR
O'Connor et al., 2017 [34]	RCT	EGRT:13 EGET:13 CG:20	F/M	54.6 ± 10.6	NR
Senthil et al., 2020 [35]	RCT	EG:53 CG:51	F/M	36.2 ± 8.6	NR
Riess et al., 2014 [36]	RCT	EG:16 CG:15	F/M	56.9 ± 12.2	NR
Greenwood et al., 2015 [37]	RCT	EGRT:20 EGET:20 CG:20	F/M	54.6 ± 10.6	NR
Karelis et al., 2016 [38]	RCT	EG:10 CG:10	F/M	45.3 ± 14	2 to 18 (months)
Crepaldi et al., 2024 [39]	RCT	EG:8 CG:7	F/M	52 ± 10	NR
Billany, 2025 [40]	RCT	EG:25 CG:25	F/M	49 ± 13	NR

RCT: randomized controlled trial, NRCT: non-randomized controlled trial, F: female, M: male, NR: not reported, EG: experimental group, CG: control group, EGRT: experimental group resistance training, EGET: experimental group endurance training.

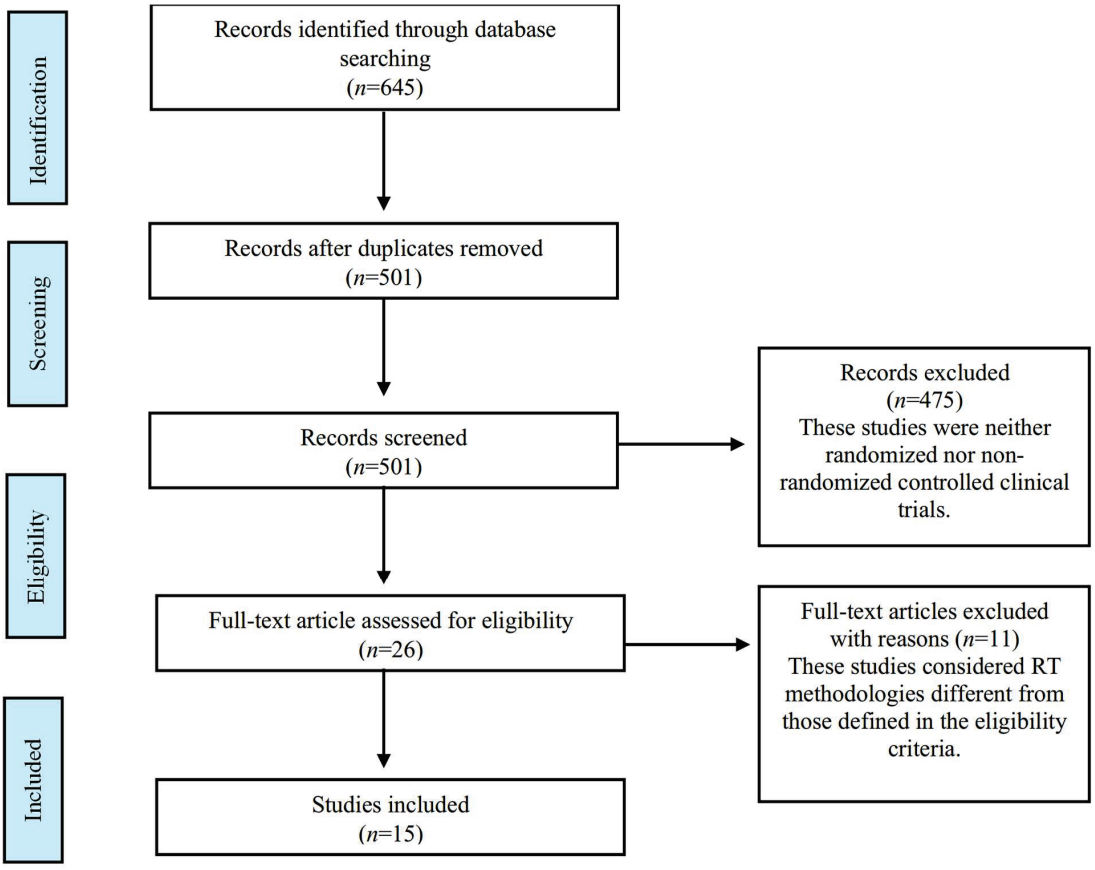


Figure 1. PRISMA flow diagram.

3.3. Synthesis of Results

Table 2 summarizes the exercise prescription details. Three studies focused on RT [27,32,38], two compared endurance and RT [34,37], and the remaining implemented concurrent training [26,28–31,33,35,36,39,40]. Training frequency ranged from three to five sessions per week, the intervention duration ranged from 2.5 to 12 months, and session length ranged from 30 to 90 min. Six studies used light dumbbells, body weight, and elastic bands [28–31,33,35], while four included machine-based exercises [27,37,38,40]. Four studies did not specify the exercise type [26,32,34,36]. The number of exercises per session ranged from 5 to 12.

Table 2. General components of training program load.

Study	Training Type	Frequency (Days of Week)	Duration (Months)	Session Duration (Minutes)	Number of Exercises	Types of Exercises
[26]	CT	3	12	60	5	NR
[27]	RT	2	2.5	60	NR	Exercises involving the upper and lower limb such as leg press, rowing pulley, leg curl, flymachine, machine calf raises, knee extension and core work.
[28]	CT	3	3	60 a 90	NR	Exercises for upper and lower extremities and abdominal muscles using free weights or body weight.
[29]	CT(SP)	3	6	60 a 70	3 a 6	Dynamic muscle-strengthening exercises.
[30]	CT	3	3	35	5	Exercises with free weights.
[31]	CT (SP)	3	6	60 a 90	6	Exercise with body weight.
[32]	RT	2	3	60	NR	NR
[33]	CT	2	6	30	2 a 3	Exercises with light dumbbells, body weight and elastic bands.
[34]	ET and RT	2	3	NR	NR	NR
[35]	CT	2	3	NR	NR	Exercises with the use of gravity and own body weight in phase 1 and exercises were performed for quadriceps with external loads for phase 2.
[36]	CT	5	3	NR	NR	NR
[37]	ET and RT	1	3	60	8	Bench press, latissimus pulldown, bicep curl, triceps pull down, leg press, knee extension, hamstring curl, and calf raises
[38]	RS	3	2.5	45 a 60	7	Leg press, chest press, lat pulldowns, shoulder press, arm curls, triceps extensions, and sit-ups
[39]	CT	3	6	60	5	Leg extension, pectoral machine, lat machine, leg curl, and abductor machine.
[40]	CT (SP)	5	3	60	12	Squat, hip abduction, lunge, calf-raise, side-lunge, bicep-curl, bent-over row, reverse-fly, lateral-raise, chest-press, side-bends, and standing trunk rotation.

RT: resistance training, ET: endurance training, CT: concurrent training, SP: without face-to-face support, NR: not reported.

Table 3 details the periodization characteristics. Intensity was primarily controlled using a percentage of one-repetition maximum (1RM) [26,32,35–38,40]. Other methods included OMNI scale [30], maximum heart rate (MHR) [28], and maximum repetitions [27]. Sets ranged from two to eight, repetitions from 10 to 20, and rest intervals from 1 to 5 min. Load progression was based on intensity, volume, or exercise complexity. Execution velocity was reported in one study [30] using self-perception.

Table 3. Specific components of training program load.

Study	Intensity	Sets	Repetitions	Rest Time Between Sets (Minutes)	Progressive Load	Velocity
[26]	35% 1RM	2	20	NR	An increase in load is indicated at 6 months but no further information is given.	NR
[27]	10 RM	3	10	1	Increased volume was progressively throughout the training program coming to complete four sets of 10-RM.	NR
[28]	40 al 65% MHR	NR	NR	NR	An increase in intensity is indicated based on the response of each participant but the way in which it was performed is not mentioned.	NR
[29]	NR	2	8 a 10	NR	The load was adjusted with changes in positions during the development of the exercises and including balls, bands, and dumbbells.	NR
[30]	6 A 7 (OMNI)	2	10	1	NR	Controlled by self-perception.
[31]	NR	8	10	1	NR	NR
[32]	50% 1RM	NR	10 a 15	NR	An increase of 5 to 10% of 1RM is indicated but the moment in which it was performed is not specified.	NR
[33]	NR	NR	10	NR	It is mentioned that first the number of repetitions was increased, then the number of sets was increased from one to two, and finally the resistance levels of dumbbells or elastic bands were increased.	NR
[34]	NR	NR	NR	NR	NR	NR
[35]	50 al 85% 1RM	NR	10	NR	Resistance was increased in a graded manner at a rate of 5% to 10% of the previous load.	NR
[36]	50% 1RM	2	10	NR	The intensity increased by 5–10% when two sets of 15 repetitions were performed while adhering to strict technique.	NR
[37]	80% 1RM	1 a 3	8 a 10	3	The one-repetition maximum was reassessed monthly, and the program was adjusted accordingly.	NR
[38]	80% 1RM	3	10	1 a 5	Weekly increase based on ability to maintain prescribed number of repetitions	NR

Table 3. *Cont.*

Study	Intensity	Sets	Repetitions	Rest Time Between Sets (Minutes)	Progressive Load	Velocity
[39]	NR	NR	NR	NR	It is indicated that the progression ranged between 40 and 50% and 65–75% of a person's maximum exercise capacity, but it is not indicated with which load component these percentages were estimated.	NR
[40]	60%1RM	2	10	1	The progression of the load was achieved by increasing the number of series per session.	NR

1RM: one-repetition maximum, MHR: maximum heart rate, OMNI: Perceived Exertion Scale for Resistance Exercise, NR: no reported.

4. Discussion

This review provides a comprehensive analysis of the characterization of load components in RT programs for kidney transplant recipients. Based on the analysis of thirteen studies, certain trends were identified; however, one of the main findings of this review was the high variability in exercise prescription and the lack of standardized criteria for load dosing.

Regarding the type of training, most of the reviewed studies suggest a concurrent training methodology [26,28–31,33,35,36,39,40]. This approach integrates RT as a fundamental component of the training session while complementing it with cardiorespiratory exercises. In fact, evidence from other populations indicates that concurrent training does not impair muscle hypertrophy or maximal strength development [41]. However, gains in explosive strength may be attenuated, particularly when cardiorespiratory exercise and RT are performed within the same session [42]. Moreover, concurrent training appears to be an effective exercise methodology for enhancing motivation and adherence, particularly among sedentary individuals with no prior experience in structured training programs [43–45]. This could explain its frequent implementation in the transplant population.

Load intensity is a critical variable in RT load dosing across different populations [46–49]. Among the studies included in this review, six used %1RM to control this variable [26,32,35–38,40], making it the most commonly employed indicator. However, the reported training intensities ranged from 30% to 80% of 1RM, highlighting a lack of conceptual clarity regarding the optimal intensity range for kidney transplant recipients.

Regarding volume, the number of exercises per session ranged from five to eight, the number of sets varied between two and eight, and repetitions ranged from 10 to 20. Similarly to intensity, these broad ranges reflect the absence of conclusive scientific evidence establishing precise training volumes to induce specific chronic adaptations, as has been determined for other populations [50,51]. Similarly, it was observed that rest intervals between sets is a fundamental variable for specific adaptations such as hypertrophy development [52] were not reported in nine of the reviewed studies [26,28,29,32–36,39]. This suggests that the importance of this variable has been overlooked when designing training protocols for transplant populations.

Among the load components, execution velocity has received the least attention in this population, with only one study reporting its use [30]. In contrast, research in other populations (i.e., older adults) has demonstrated that high-speed resistance training is effective for improving overall health outcomes [53]. It is worth mentioning that movement

velocity is an accurate approach for prescribing RT, offering multiple advantages such as controlling intensity from the first repetition of a set [54–56] and regulating volume based on velocity loss [20,57]. Controlling this variable eliminates many of the inconsistencies associated with traditional RT methods of RT [18]. If a linear position transducer is not available, perceived exertion and movement velocity scales serve as valid, economical, and practical tools for assessing RT load progression and complementing other training monitoring variables, although familiarization remains key [58].

Regarding exercise selection, six of the reviewed studies recommended the use of light dumbbells, body weight exercises, and elastic bands [28–31,33,34]. A possible rationale for this recommendation is the ease of execution, particularly for individuals with limited RT experience, a common characteristic in this population.

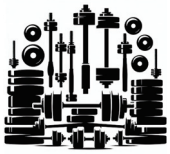
One of the main limitations of this study is that only 15 out of the 501 initially identified studies were included. While the strict eligibility criteria ensured the quality of the analyzed studies, they may have excluded some training programs developed for this population. It is important to note that the scope of this review was limited to the load components of strength training programs; the effects of these interventions on the outcome variables assessed in each study were not analyzed. Additionally, certain strength training methodologies, such as suspension exercises, were not considered.

Considering the absence of standardized criteria for periodizing load components in kidney transplant recipients, Table 4 summarizes the most frequently reported elements in the reviewed studies. These elements can serve as a foundation for exercise professionals in designing training programs for this population.

Table 4. General recommendations for prescribing RT for kidney transplant recipients.

Load Component	Recommendation for This Component
Training Type 	RT might be complemented with concurrent training. Adherence is crucial.
Frecuency and session duration 	The recommended frequency is at least twice per week. Each session should last a minimum of 30 min.
Types of Exercises 	Bodyweight exercises and light dumbbells are the most recommended modalities.
Number of exercises 	The number of exercises per session ranges from five to eight.

Table 4. *Cont.*

Load Component	Recommendation for This Component
Intensity of load 	Intensity can be regulated as a percentage of 1RM, with work ranges varying between 30% and 80% of 1RM.
Training volume 	Training volume includes two to eight sets per exercise, with repetitions ranging from 10 to 20 per set.
Rest time between sets 	Rest intervals between sets vary between one and five minutes.
Progressive load 	Load progression is achieved by increasing the intensity, volume, or technical difficulty of the exercises.
Execution velocity 	Execution velocity of movements has not been extensively reported in this patient population.

Future Directions

One of the most significant insights derived from this review is the recognition that, while a substantial body of scientific evidence supports the beneficial effects of structured exercise programs on various health outcomes, notable methodological limitations continue to persist within the design and implementation of these training protocols. These shortcomings highlight the need for a more rigorous and standardized approach to exercise prescription, particularly in clinical populations where individualized interventions are crucial. In this regard, fostering interdisciplinary collaboration among nephrologists, sports medicine physicians, and exercise professionals presents a promising avenue for addressing these challenges. By integrating their respective expertise, these specialists could contribute to the development of more precise, evidence-based, and systematically structured training regimens tailored to the specific physiological and medical needs of patients. Such an approach would not only enhance the efficacy of exercise interventions, but also ensure their safety and long-term adherence.

The heterogeneity of the implemented programs hinders the establishment of specific and detailed parameters for load prescription. However, the common elements identified

can serve as a foundation for exercise professionals to design more structured and effective training plans. Future research should focus on developing more rigorous protocols supported by robust methodological frameworks that include well-defined exercise parameters, appropriate control conditions, and standardized outcome measures. Additionally, it is essential to determine the optimal exercise modalities, intensities, and durations that maximize therapeutic benefits in patients with various health conditions. Strengthening the scientific foundation in this field will facilitate the integration of structured exercise as a fundamental component of clinical care, enhancing both the effectiveness of interventions and the overall health and well-being of patients.

5. Conclusions

This scoping review described the general characteristics of the load components in RT programs for kidney transplant recipients. The findings highlight a lack of standardized criteria in the prescription of fundamental periodization variables; however, several recommendations based on available evidence are given regarding intensity, volume, and load progression. Additionally, movement velocity remains an overlooked component in the design of strength training programs for this population.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/sports13050153/s1, Table S1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR) Checklist; Table S2. Detailed search strategy in each specific base.

Author Contributions: Conceptualization, J.C.P. and C.L.; methodology, L.S.-G. and C.C.; formal analysis, B.T. and J.C.P.; investigation, J.C.P. and L.A.C.; resources, J.C.P. and E.P.; data curation, L.A.T.; writing—original draft preparation, J.C.P.; writing—review and editing, D.A.B. and L.A.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: This study was conducted in accordance with the Declaration of Helsinki and approved by the Fundación Universitaria del Area Andina (19 April 2024).

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

Data Availability Statement: The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding author.

Conflicts of Interest: D.A.B. has conducted academic-sponsored research on resistance training, is a delegate of the NSCA LATAM in Colombia (https://www.nscalatam.com/dbss) (accessed on 7 March 2025) and has received honoraria for selling linear position transducers and speaking about exercise sciences at international conferences and private courses. The other authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

RT	Resistance training
1RM	One-repetition maximum
OMNI	Perceived Exertion Scale for Resistance Exercise
MHR	Maximum heart rate

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Review

Return to Physical Activity in Individuals with Surgical Stomas: A Scoping Review

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Abstract: In surgically treated individuals with surgical stomas, the return to physical activity is an indicator of quality of life that reflects their well-being. With the aim of synthesizing the available evidence regarding the return to physical activity in individuals with surgical stomas, a scoping review was developed following the methodological approach of the Joanna Briggs Institute and the Preferred Reporting Items for Systematic reviews and Meta-Analyses for Scoping Reviews criteria. Searches were conducted in Medline (PubMed), Scopus, Web of Science, Cinahl, and Lilacs, as well as the meta-search engines TripDatabase and Epistemonikos, using MeSH terms. Included studies were written in Spanish, English, Portuguese, and German, without any limitation on the year of publication. A total of n = 15 studies was included (n = 2 qualitative; n = 2 case reports; n = 1 case series; n = 1 cohort; n = 8 cross-sectional; and n = 1 randomized clinical trial), which showed variability in the quality of the designs. The qualitative studies explored themes such as motivation, beliefs about physical activity, and other lifestyle factors. The case reports described physiological, psychological, and functional implications of returning to physical activity for specific individuals after ostomy surgery. Quantitative studies evaluated the effects of different types of physical activity on quality of life and tolerance to physical activity in these individuals, employing various measurement instruments. In conclusion, the evidence on returning to sports and physical activity after stoma surgery is limited and varied. While studies highlight the importance of social support and self-confidence, they generally lack rigor and primarily focus on adults and oncology patients. There is a need for more research to establish clear guidelines on physical activity type, frequency, and intensity to ensure safe and beneficial outcomes for individuals with stomas.

Keywords: exercise; return to sport; surgical stomas; ostomy; quality of life; review

1. Introduction

Cancer is a disease characterized by the uncontrolled growth and spread of abnormal cells within the body [1]. Colorectal cancer, in particular, affects the cells of the colon or rectum. According to the World Health Organization (WHO), colorectal cancer is the fourth most common type of cancer globally, with a surgical intervention rate exceeding 90%, often requiring a temporary or permanent ostomy [2]. It is estimated that colorectal cancer accounts for 50% of intestinal stomas [3]. Furthermore, bladder cancer is the second most common urinary tract malignancy, mostly affecting patients aged 65 years or older [4], and may also require the creation of urinary stomas. However, there are a number of non-oncological pathologies or complications of diseases that require the creation of a stoma in both adults and children [5].

An ostomy is a surgically created opening between a hollow organ and the body's surface, primarily intended to divert intestinal contents [6]. There are two main types of intestinal stomas: colostomies and ileostomies. Colostomies are classified as permanent

or temporary based on the duration or reversibility of the ostomy, and as ascending, transverse, descending, or sigmoid according to the part of the colon used. Ileostomies can also be permanent or temporary and, depending on the surgical technique, may consist of a conventional or Brooke ileostomy, a continent ileostomy, or an ileoanal reservoir (J-pouch or pelvic pouch) [7]. In relation to the urinary stomas, the urinary diversion can be divided into two types according to their urine reservoir manipulation: continent reservoirs and non-continent reservoirs [5].

The creation of a stoma involves economic, physical, psychological, and social challenges for individuals, significantly affecting their quality of life (QoL). Patients with a stoma often experience a lower QoL compared to those without one [3]. QoL has been described as the overall well-being of an individual or community, considering their health and level of happiness rather than focusing exclusively on economic factors. Additionally, it can be understood as the patient's perception of their physical, psychological, social, and spiritual health [7]. Changes in the QoL of individuals can result in issues such as anxiety, sleep disturbances, and difficulties in interpersonal relationships [8]. Living with an ostomy leads to changes in body image and functionality, impacting personal aspects such as sexuality, as well as occupational and social factors. These include challenges in daily activities, managing stoma-related complications, finding privacy to empty the pouch, and coping with odors from fecal leaks [9,10]. In these individuals, it is crucial to promote and develop their self-care capabilities to reduce such clinical complications and social health issues [3]; among these interventions, actions aimed at physical activity (PA) should be included [10].

PA is essential to enhancing QoL as it integrates physical, mental, and social dimensions to promote and sustain an active, healthy lifestyle. PA is a comprehensive term encompassing various forms of movement, defined as any bodily movement produced by skeletal muscles that results in energy expenditure above basal levels. Exercise and sport are distinct subcomponents of PA. Exercise typically involves structured, purposeful, and repetitive isometric or isotonic movements aimed at maintaining or improving physical fitness [11]. In contrast, sport generally refers to competitive forms of PA, which are regulated by rules and guidelines. Beyond its physical benefits, PA exerts positive effects on mental health by reducing stress levels and promoting psychological relaxation. Moreover, it provides social benefits, particularly when performed in group or team-based settings [11].

In individuals with stomas, the return to PA may be beneficial for aerobic fitness, cancer-related fatigue, and health-related QoL [12,13], including physical functioning, role function, social functioning, and fatigue [13]. However, clinical outcomes related to the number of complications, incidence of parastomal hernias, or prolonged hospital stays have not yet confirmed these positive effects [3]. In this context, while the return to PA is often used as an indicator to assess orthopedic clinical outcomes in sports medicine, it is frequently interpreted simply as the resumption of PA [14]. Most studies have focused on athletes who have already returned to competitive sports or resumed training. However, the lack of standardization or structured programs during this return affects the accurate evaluation of outcomes [15,16]. Thus, the available literature on returning to sports after surgery is extensive, particularly in the areas of sports traumatology [17–20] and pediatrics [21,22]. However, the topic of resuming PA in individuals with stomas remains unexplored. Currently no reviews on PA and individuals with stomas have been developed. To address this gap, a scoping review has been conducted to examine the existing scientific literature. The research question guiding this review is: What evidence is available regarding the return to PA in individuals with surgical stomas within the context of post-surgery rehabilitation? The aim was to synthesize the existing evidence regarding the return to PA in individuals with surgical stomas.

2. Materials and Methods

2.1. Design

A scoping review was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses for Scoping Reviews (PRISMA-ScR) criteria [23]. To develop the review approach, the methodological proposal of the Joanna Briggs Institute (JBI) was followed. The research question followed the structure comprised of Population (P): Individuals with surgical stomas; Intervention (I): Return to PA; and Outcome (O): Post-surgery rehabilitation (in terms of physical and mental health). The review protocol was registered on 1 November 2023, prior to starting the review process, in the Open Science Framework (OSF), and can be accessed at the following link: https://osf.io/7yv6d/ (accessed on 1 July 2024).

2.2. Information Sources

As a first step, the scientific literature was consulted to determine the existence or not of systematic reviews addressing the topic and a search was conducted in PROSPERO to find registered protocols corresponding to surveys that answered the same research question. After this initial query, searches were conducted in the following databases: Medline (through PubMed), Scopus (through Scopus-Elsevier), SCI Expanded (trough Web of Science [WoS]), Cinahl (through EbscoHOST), and Lilacs (through Virtual Health Library). Searches were also conducted through the meta-search engines TripDatabase and Epistemonikos; records retrieved from these latter sources were considered as free searches.

2.3. Search Strategies

The searches were conducted between 2023 October and 2024 March using the MeSH terms: "return to sport", "exercise", "sports", "surgical stomas", "ostomy", "colostomy", "ileostomy", "enterostomy", "cecostomy", "duodenostomy" and "jejunostomy", or entry terms combined with the Boolean operators AND and OR. The searches were performed by one of the researchers (A.-V.M.-J.) and verified by a second (C.-A.R.-S.) using PRISMA-S for search extension [24]. The final search strategy established was adapted to each of the databases (Supplementary Table S1).

2.4. Eligibility Criteria

Inclusion criteria were as follows: According to the population: Adults and children with surgical stomas who have addressed the return to PA. According to the study design: Publications with any methodology (qualitative or quantitative) and design (experimental, observational, or qualitative) were included, as well as case studies and case series. These publications were available in Spanish, English, Portuguese, and German, with no limits on the year of publication. The broadness of these criteria is due to the fact that the review is exploratory with the purpose of finding out the state of the science on this subject. Exclusion criteria were as follows: According to the study design: Publications that did not correspond to research studies, such as opinion articles, editorials, and letters to the editor. Grey literature and research study protocols were also excluded.

2.5. Screening Process

After performing the searches, duplicate records were eliminated and screened by title and abstract. The full-text documents of the selected records were then retrieved to assess their eligibility according to inclusion and exclusion criteria. The JBI critical appraisal tools appropriate to each design were used. Screening was performed independently by two reviewers (A.-V.M.-J. and C.-A.R.-S.) and, in case of discrepancies, a third reviewer decided (H.G.-d.l.T.). As a scoping review, the critical appraisal process was not used to eliminate low-quality studies, but to identify and establish the quality of the included studies [25]. A pilot phase was conducted with a sample of records to assess the adequacy of the process. One reviewer applied the specific JBI tool to each design, while a second

reviewer independently verified the accuracy of the extracted data. The item-by-item quality assessment from JBI is available as Supplementary Table S2.

2.6. Data Extraction

The primary outcome variable of the study was the return to PA in individuals with a stoma. However, data on the return to PA were also extracted when reported as a secondary outcome. As a secondary outcome variable, information on QoL and body composition was extracted when reported. Bibliometric (authors, year, and study design) and sociodemographic (country, age of participants, type of disease, setting, and type of stoma) variables from the studies included were extracted, as well as the descriptive (data collection, sample and patients characteristics, themes and sub-themes, measuring instruments, and PA characteristics), and statistical data (mean, standard deviation, percentage, odds ratio, confidence intervals, effect sizes, or other additional statistical results). Data were exported to an Excel® (version: 16.17) file, with methodological support provided by the Mendeley® reference manager software (version: 2.121.0). Data extraction was carried out independently and blinded by two researchers (A.-V.M.-J. and C.-A.R.-S.), and a third reviewer settled any and all discrepancies (H.G.-d.l.T.). When necessary, authors were contacted to complete the information that was not retrieved. A pilot phase of the data extraction process was conducted using a sample of studies through the development of a data extraction table in Excel®, which incorporated the key information outlined above. Additionally, a free-text field was included to capture any unexpected or supplementary data. Initially, one reviewer performed the data extraction, while a second reviewer independently verified the accuracy of the extracted data for each study design group.

3. Results

A total of n = 1802 records was identified. After removing duplicates (n = 921), the number of records that were screened by title and abstract was n = 881, excluding n = 844 records; the remaining n = 37 were retrieved for quality assessment and full-text screening, with n = 15 studies included in the review, as shown in Figure 1.

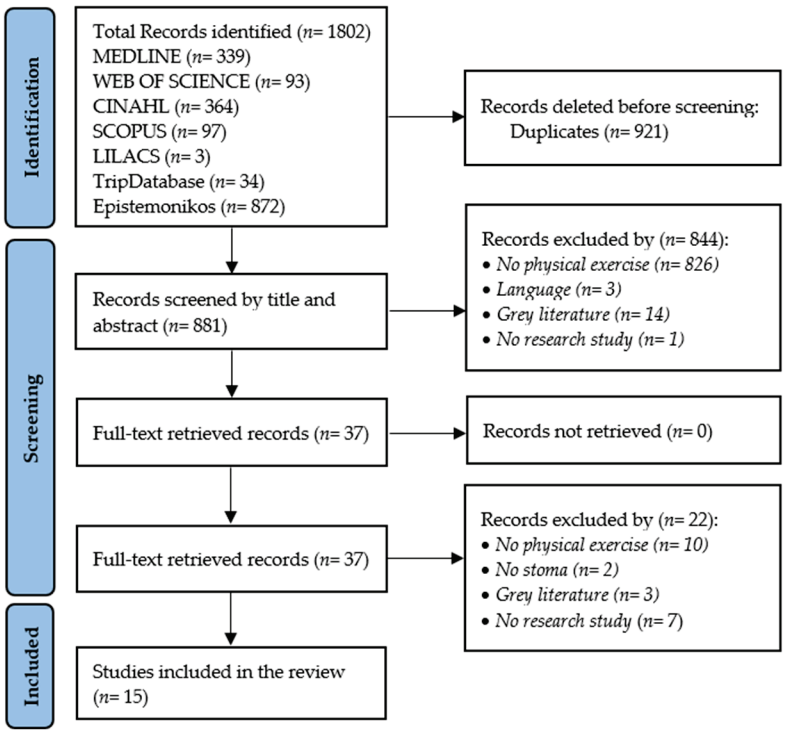


Figure 1. Flowchart of the studies included in the review.

Among the studies excluded, $n = 22$ did not meet the inclusion criteria (Supplementary Table S3).

Table 1 shows the general characteristics, aims, conclusions, and methodological quality after applying the JBI critical appraisal tools.

Table 1. General characteristics of included studies.

Author (Year); Design; Country (Age of Participants) Type of Disease	Aim	Conclusions	JBI [1] Quality Items (%)
Park et al. (2023) Cross-sectional; USA (Adults) oncology/non-oncology [26]	To determine rates and risk factors for parastomal hernias in patients with permanent ostomies.	Parastomal hernia rates remain high in current surgical practice. There is an association between PA [2] and the presence of parastomal hernia, with a higher rate among those who exercise less.	5/8 (62.5)
Goodman et al. (2022) Cross-sectional; UK (Adolescents/Adults) Oncology/Non-oncology [27]	To identify subgroups in the QoL [3] of people with stomas. To assess whether belonging to these groups is associated with demographic, clinical, and PA characteristics.	Some latent profiles associated with demographic and clinical variables were identified, but additional variables should be identified in the future to provide the basis for targeting and tailoring future interventions to specific subgroups of people with a stoma.	5/8 (62.5)
Krogsgaard et al. (2022) Cross-sectional; Germany (Adults) Oncology [28]	To examine the level of PA and explore factors influencing PA in cancer survivors with a stoma.	Half of patients met or exceeded the guideline recommendations. Of the patients who did not meet the recommendations, some could meet them by slightly increasing moderate or vigorous activity.	8/8 (100)
Mo et al. (2021) Cross-sectional; USA (Adults) Oncology [29]	To describe lifestyle behaviors and their relationships with health-related QoL in cancer survivors with ostomies.	Improved QoL is associated with adherence to PA guidelines among cancer survivors with ostomies. Results have clinical relevance for ostomy self-care and establishing lifestyle recommendations.	8/8 (100)
Saunders and Brunet (2019) Qualitative; Germany (Adults) Oncology [30]	To explore the experiences of rectal cancer survivors with a stoma and the impact on their engagement in PA.	The stories provided experiences related to cancer and the stoma, highlighting reasons for and barriers to PA. The results helped to identify useful strategies for those learning to be physically active with a stoma.	7/9 (77.7)
Lowe, Alsaleh, and Blake (2019) Cross-sectional; UK (Adults) Not specified [31]	To assess PA levels in adults with a stoma. To investigate the relationship between activity levels, exercise self-efficacy, perceived benefits and barriers to exercise, depression, body image, and stoma-related QoL.	Most participants were physically inactive. Interventions that reduce barriers to exercise and support self-efficacy in people with stoma may help them increase their PA levels, as well as reduce the risk of chronic diseases associated with sedentary lifestyles.	8/8 (100)
Kindred et al. (2019) RCT; USA (Adults) Oncology [32]	To examine the relationship between changes in fitness and body fat with changes in body esteem among colorectal cancer survivors after testing the effects of a PA intervention.	Improving physical fitness and body composition may enhance self-esteem among these cancer survivors; however, there are differences according to gender and stage of disease.	11/13 (84.6)

Table 1. *Cont.*

Author (Year); Design; Country (Age of Participants) Type of Disease	Aim	Conclusions	JBI [1] Quality Items (%)
Russell (2017) Cross-sectional; UK (Adults) Oncology/Non-oncology [33]	To investigate the physical health and well-being of people living with stomas in the UK.	There are gaps in care regarding advice on PA, abdominal exercises, and prevention and treatment of stoma hernias. More research and training for patients and healthcare professionals is needed.	2/8 (25)
Russell (2017) Cross-sectional; UK (Adults) Oncology/Non-oncology [34]	To investigate the physical health and well-being of people living with stomas in the UK.	PA levels drop significantly after stoma surgery; the vast majority of people living with a stoma do not meet PA guidelines. Those diagnosed with cancer or parastomal hernia are even less active.	2/8 (25)
Krouse et al. (2017) Cross-sectional; USA (Adults) Oncology [35]	To examine the relationships between PA, health-related QoL, and bowel function in rectal cancer survivors.	Meeting or exceeding PA guidelines was associated with increased QoL. The results suggest that women may benefit from increased PA, while men with ostomies may face challenges that require further study. There is a need to identify PA strategies that improve compliance and benefits in patients.	8/8 (100)
Wiskemann et al. (2016) Case report; Germany (Adult) Oncology [36]	To report on how a firefighter with rectal carcinoma and an ostomy was trained to recover fitness for work.	Colorectal cancer survivors with ostomies may be able to recover fitness for demanding physical tasks, such as firefighting, through an individualized and supervised training program.	8/8 (100)
Sica (2016) Case report; UK (Adult) Oncology [37]	Not reported.	Having a stoma and recovering from major surgery can be a challenging and lengthy process. Finding the right pouching system is an integral part of recovery and can help give subjects the confidence to start resuming previous activities, including sport.	5/8 (62.5)
Anderson et al. (2013) Qualitative; UK (Adults) Oncology [38]	To explore perceived needs for advice on diet, activity, and beliefs about the role of lifestyle in reducing disease recurrence.	Lifestyle changes can lead to perceived blame and stigmatization. Personalized, evidence-based counselling on lifestyle choices appears to be a much-needed part of care planning and should be incorporated into survivorship programs.	7/9 (77.7)
Courneya et al. (1999) Cohort; Canada (Adults) Oncology [39]	To examine the relationship between physical exercise and QoL in patients with colorectal cancer.	Small changes in exercise from pre-diagnosis to post-surgery are positively associated with QoL in patients with colorectal cancer, but experimental research is needed before definitive conclusions can be drawn.	5/11 (45.4)
Isaacs (1984) Case series; UK (Adults) Oncology [40]	To detail fluid and electrolyte balance data in a team of ileostomized marathon runners who regularly run long distances.	Healthy ileostomates after adequate training are successful marathoners, but the prevalence of a slight depletion in sodium level in ileostomates suggests that it may also be advisable for them to take glucose or electrolyte solutions when competing at any ambient temperature or when preparing for a marathon in hot environments.	6/10 (60)

[1] JBI: Joanna Briggs Institute; [2] PA: Physical Activity; [3] QoL: Quality of Life.

The included studies comprised qualitative (n = 2), cohort (n = 1), cross-sectional (n = 8), case studies (n = 2), case series (n = 1), and randomized clinical trial (RCT) (n = 1) designs, showing variability in the quality of the studies. Most of them were conducted in the United Kingdom (UK) (n = 7), United States of America (USA) (n = 4), and Germany (n = 3), with n = 1 study from Canada. Only the study by Goodman et al. [27] included adolescent patients, while none involved children. Regarding the type of disease, all studies included cancer survivors, except Park et al. [26], Goodman et al. [27], and Russell [33,34], which also involved non-cancer patients. Finally, Lowe, Alsaleh, and Blake [31] did not specify the underlying pathology that led to the stoma in their study.

Two studies did not clearly specify the qualitative approach in their methodology and utilized different data collection techniques. The themes explored included motivation, beliefs about PA, and other lifestyle factors. The emergent themes and sub-themes are shown in Table 2.

Table 2. Qualitative studies included in the review.

Author (Year) Design	*N* (Type of Stoma) Data Collection	Themes and Sub-Themes
Saunders and Brunet (2019) Qualitative (No specified approach) [30]	*N* = 15 (Not specified) Semi-structured interviews	*Themes*: Reasons for physical activity *Sub-themes*: Fun, health benefits (mental and physical), sense of accomplishment, weight control, sense of normalcy, taking time for themselves away from daily responsibilities
		Themes: Physical activity discourages *Sub-themes*: Negative side effects of cancer and treatments, uncertainty in unfamiliar environments, physical restrictions, fear of injury, unclear orientation, stoma, shyness in public and private, negative previous experiences
		Themes: Implications for practice *Sub-themes*: Social support and support networks, counseling, previous experiences, experimentation, safe environment, skills and confidence
Anderson et al. (2013) Qualitative (No specified approach) [38]	*N* = 40 (Not Specified) 6 focal groups	*Themes*: Beliefs about the role of diet, physical activity and lifestyle in reducing long-term disease risk
		Themes: Health maintenance actions
		Themes: Interest in receiving guidance on diet, activity and lifestyle to reduce risk and disease progression
		Themes: What are the forms, schedules and modes of guidance on nutrition, physical activity, and lifestyle?

On the other hand, two case report studies [36,37] and one case series report [40] describing the evolution process of the ability of these individuals to return to PA after the ostomy were included, in which physiological, psychological, and functional implications were addressed, as shown in Table 3.

Table 3. Cases studies included in the review.

Author (Year) Design	Type of Stoma Patient Characteristics	Case Results
Wiskemann et al. (2016) Case report [36]	Permanent colostomy. Male, 44 years old. Rectal adenocarcinoma. Firefighter. Performed aerobic exercise (running, swimming, rowing) and resistance (weight training with weights and machines). Since the diagnosis has been inactive. To return to work must pass ergometric tests. Training program, 9 months: 0–2 preparation: 1.3 sessions/week. 2–4 supervised individual training: 2.3 sessions/week. 4–6: group training: 3 sessions/week. 6–9: autonomous training.	*European Organization of Research and Treatment in Cancer Questionnaire about Quality of Life 30 (EORTC QoL 30)*: Score: 66.67. Pain and diarrhea decreased 50%, insomnia and loss of appetite disappeared stool control at 9 months. Subscales showed reduction in fatigue (30% mental fatigue, 64% physical fatigue) during first 4 months. Distress was reduced 50% at 9 months. At baseline, 6 physical problems (pain, fatigue, sleep, dry/itchy skin, dry/obstructed nose and sexual problems), 2 emotional problems (worries, sadness), and 1 family problem (partner). At 9 months, only 2 problems remained in the physical section (indigestion, dryness, nasal obstruction).
Sica (2016) Case report [37]	Ileostomy. Woman, 28 years old. Symptoms began while she was studying to become an elementary school teacher. Prior to surgery she performed jazz, street, and contemporary dance. After stoma, she undertook running and classes at a local gym.	*Back to the sport*: When started to get her strength back, she began trying different classes at a local gym. Although she feels good, she tries to do the exercises in the least harmful way possible.
Isaacs (1984) Case series [40]	Ileostomy. Five men aged 22, 37, 40, 42, 56, and 56. Due to ulcerative colitis participated in the 1983 London Marathon. Questionnaires about ileostomy function, diet, training program, and experience. Urine and ileostomy secretion data were collected 3–4 h before the race and 5–6 h after. Before, they were weighed with running equipment, and blood pressure, heart rate, and a venous blood specimen were obtained. Procedure repeated within 5 min of the end of the race.	*Weight loss:* Between 1 and 3 kg. *Ileostomy flow*: The ileostomy discharged volume and sodium concentration showed no change during the race, but potassium concentration increased in contrast to the unchanged urine. Total water and potassium losses during the race were minimum. *Plasma biochemistry***:** Sodium levels lower. Urea and total protein higher compared to non-ostomized runners. After the race, increased blood urea, uric acid, and bilirubin occurred in all subjects.

Regarding the quantitative studies, only Mo et al. [29] reported 150 min of moderate exercise or 75 min of intense exercise. Lowe, Alsaleh, and Blake [31] mentioned walking, while Kindred et al. [32] referred to strength exercises. The remaining studies did not specify the type of exercise. PA was evaluated using different validated instruments, such as the International Physical Activity Questionnaire (IPAQ) short form [26,31], the Excess Benefits and Barriers Scale (EBBS) [31], the Body Esteem Scale (BES) [32], and the Godin Leisure-Time Exercise Questionnaire (GLTEQ) [39]. Additionally, modified instruments were used, including Self-Efficacy to Perform Self-Management Behaviors [29] and Self-Efficacy for Exercise (SEE) [31], as well as ad hoc instruments [33,34], as shown in Table 4.

Table 4. Quantitative studies included in the review.

Author (Year) Design	Sample Size (*N*) Type of Stoma PA [1]	Instruments	Statistical Data
Park et al. (2023) Cross-sectional [26]	*N* = 443 Male: *n* = 266 (61.9%); Female: *n* = 165 (37.9%); Non-binary *n* = 1 (0.2%). Urostomy: *n* = 212 (47.9%); Colostomy: *n* = 132 (36.1%); Ileostomy: *n* = 99 (22.3%) Parastomal hernia: No: *n* = 327 (75.3%); Yes: *n* = 129 (29.3%) PA: Not reported	**QoL [2]:** *QoL scale*: Dimensions: 4; Reliability: Not reported; Likert scale: 4 items. **PA:** *International PA Questionnaire (IPAQ) Short Form:* Reliability: Not reported; Measure expressed in metabolic equivalents (MET minutes/week).	**QoL:** *QoL scale*: Total Lower if hernia (U = 11.99; p = 0.004). **PA:** *International PA Questionnaire Short Form:* PA: U = 8154; *Mean* = 579 (yes hernia) vs. 1689 (no hernia) p = 0.001. Correlation between PA intensity and time after ostomy making (r = 0.009; p = 0.870).
Goodman et al. (2022) Cross-sectional [27]	*N* = 1528 Male: *n* = 289 (20.4%); Female: *n* = 1122; (79.1%); Miss sex: *n* = 8 (0.6%) Ileostomy: *n* = 956 (67.7%); Colostomy: *n* = 444 (31.3%); Miss stoma: *n* = 19 (1.3%) PA: Not reported (number of days with exercise of 30 min or more on which the respiratory rate increased should be noted).	**QoL:** *Stoma Quality of Life (SQoL):* 19 items in 5 subscales (Work/social function; Sexuality and body image; Stoma function; Economic concerns; Skin irritation). Likert scale: 5 items. Score: 0 (never)–100 (always). Reliability (α = 0.89). **PA:** (additional item): number of days with increased respiratory frequency (Range: 0–7).	**QoL:** *SQoL [Mean (SD [3])]:* Work/social function: 63.6 (23.0); Sexuality and body image: 61.5 (19.3); Stoma function: 52.8 (20.6); Financial concerns: 81.3 (28.5); Skin irritation: 47.2 (27.9). **PA:** (days/week): *Mean* = 2.6 (*SD* = 2.3); 4 profiles according to SQoL responses: Profile 1: Good QoL (*n* = 891; 62.8%); Profile 2: Some problems with QoL (*n* = 184; 13.0%); Profile 3 Low QoL (*n* = 181; 12.8%); Profile 4: Financial concerns (n = 163; 11.5%). Individuals classified in Profile 3 were less able to stoma for more than 2 years (*OR*: 0.65; 95% *CI*: 0.43–0.96; $p < 0.05$) and spend more days physically active (*OR*: 0.85; 95% *CI*: 0.78, 0.94; $p < 0.05$), but were more likely to hernia (*OR*: 3.32; 95% *CI*: 2.17–5.07; $p < 0.05$).
Krogsgaard et al. (2022) Cross-sectional [28]	*N* = 571 Colorectal cancer and stoma in Denmark Colostomy: *n* = 491 (86%); Ileostomy: *n* = 80 (14%) PA: Not reported	**QoL:** *Colostomy Impact Score:* Ad hoc scale PROMIS items: 7 (odor, leakage, stool consistency, stoma site pain, skin problems, parasternal bulging, help with stoma management) Likert scale: not reported; Score: higher score more complications; Reliability: Not reported. **PA:** Compliant (Active, very active). Non-compliant (Inactive, insufficiently active).	**QoL:** *Colostomy Impact Score:* *n* = 313 (55%) higher impact of colostomy on PA; *n* = 358 (45%) lower impact of colostomy on PA. No association between colostomy impact and level of PA (*OR*: 1.59; 95% *CI*: 1.02–2.11). **PA:** Compliant (*n* = 293; 51%): Active *n* = 108 (36.86%); very active *n* = 185 (63.13%); >300 min *n* = 76 (41%); >151 min *n* = 59 (55%); >120 min *n* = 69 (37%); 60–120 min *n* = 36 (33%). Non-compliant (*n* = 278; 49%): Inactive *n* = 44 (15.8%); insufficiently active *n* = 234 (84.17%); <30–150 min *n* = 170 (73%); <59 min *n* = 55 (24%).

Table 4. *Cont.*

Author (Year) Design	Sample Size (*N*) Type of Stoma PA [1]	Instruments	Statistical Data
Mo et al. (2021) Cross-sectional [29]	*N* = 200 Male: *n* = 108; 54%; Female: *n* = 92; 46% Colostomy: *n* = 87; 43.5%; Ileostomy: *n* = 46; 23%; Urostomy: *n* = 67; 33.5% PA: Exercise Time recommendation according to intensity: 150 min per week if moderate. 75 min per week if vigorous.	**QoL:** *City of Hope Quality of Life Ostomy (COH-QoL-O)*: Ad hoc questionnaire. Items (no scale) on diet: 8 general diet (high protein, low carbohydrate, fast food, diabetic, vegetarian, vegan, vegan, heart-healthy, no special diet); 5 broad diet (fast food, vegetarian/vegan, therapeutic/health-promoting, gastrointestinal symptom modulating, and no special diet) and a scale with 43 items Health-Related QoL with Likert scale not reported Score: 0 (worst QoL)–10 (best QoL). Reliability: Not reported. **PA:** *Self-Efficacy (SE) to Perfom Self-Management Behaviors*: Ad hoc questionnaire from the instrument (Godin Leisure-Time Exercise Questionnaire), contains 3 unscaled parts. 2 Items: "How confident do you feel you can perform gentle exercises for muscle strength and flexibility three to four times per week (range of motion, use of weights, etc.)?" and "How confident do you feel you can perform aerobic exercises such as walking, swimming or cycling three to four times per week?". Likert scale: not reported. Score: 1 (not at all confident)–10 (totally confident); Reliability: (α = 0.83). Ad hoc *questionnaire:* One question with three parts on different PA intensities. Frequency and intensity of PA for one week. Measures: light (minimal exertion, no sweating), moderate (not strenuous, light sweating) and vigorous (heart beating fast, intense sweating).	**QoL:** *COH-QoL-O:* Those who met or exceeded American Cancer Society (ACS) guidelines reported greater psychological well-being (*Mean difference* = 1.03; 95% CI: 0.19–1.9); overall QoL (*Mean difference* = 0.74; 95% *CI*: 0.04–1.4) and physical strength (*Mean difference* = 1.29; 95% *CI*: 0.17- 2.4) compared to the non-active category. The group that met but not exceeded the ACS PA guidelines had better psychological well-being and physical strength scores that exceeded the minimally important difference compared to the non-active group. Total QoL score: (Non-active: *Mean* = 6.32 (*SD* = 0.18); Low active: *Mean* = 6.71 (*SD* = 0.26); Active: *Mean* = 7.08 (*SD* = 0.26)). Physical strength: (Non-active: *Mean* = 6.15 (*SD* = 0.30); Low active: *Mean* = 6.89 (*SD* = 0.40); Active: *Mean* = 7.48 (*SD* = 0.48). **PA:** *SE:* Self-efficacy for aerobic exercise accounted for greater variance for PA time (4.9%) than ostomy type (2.5%). Patients with urostomies who met ACS PA guidelines had higher self-efficacy scores for aerobic exercise capacity (p = 0.02). Patients who met ACS PA guidelines had higher self-efficacy scores for both gentle (8.1 points out of 10) and aerobic exercise (8.7 points out of 10) compared to those who did not meet guidelines. However, the latter group of patients reported moderate self-efficacy with respect to the ability to perform gentle (6.7 points) or aerobic (6.1 points) PA. Ad hoc *questionnaire:* No differences in PA intensity and type of ostomy: Intense PA (p = 0.06): Colostomy: *Mean* = 91.3 (*SD* = 198.2); Ileostomy: *Mean* = 38.6 (*SD* = 79.6); Vigorous PA (p = 0.08): Colostomy: *Mean* = 16.2 (*SD* = 63.3); Ileostomy: *Mean* = 3.8 (*SD* = 17.1); Moderate AF (p = 0.32): Colostomy: *Mean* = 59 (*SD* = 122.3); Ileostomy: *Mean* = 31 (*SD* = 66.6).

Table 4. *Cont.*

Author (Year) Design	Sample Size (*N*) Type of Stoma PA [1]	Instruments	Statistical Data
Lowe, Alsaleh, and Blake (2019) Cross-sectional [31]	*N* = 116 (completed questionnaire *n* = 94) Male: *n* = 46; 49%; Female: *n* = 48; 51% Colostomy, ileostomy and urostomy PA: Walking	**QoL:** *Patient Health Questionnaire (PHQ-9):* Items: 9 criteria for depression (depressed mood or irritability, decreased interest or pleasure, significant weight loss or loss of appetite, changes in sleep pattern, changes in activity, fatigue or loss of energy, guilt or worthlessness, concentration, and suicidality; Likert scale: 0 (never)–3 (almost every day); Score: 5–27 (higher score indicates depression, less than 4 indicates no depression) Reliability: Not reported. *SQoL:* Items: 20 in 5 domains (stoma device; sleep; sexual activity; relationships with family and friends and social relationships). Likert scale: 1 (always)–4 (never); Score: 20–80 (higher score indicates optimal QoL). Reliability: Not reported. *Social Physique Anxiety Scale (SPAS):* Items: 12; Likert scale: 1 (not at all characteristic of me)–5 (extremely characteristic of me). Score: Maximum 60 (low scores indicate reduced physical anxiety; Reliability: Not reported. **PA:** *IPAQ Short Form:* Short version. Measures of the amount of exercise in frequency (days per week) and duration (hours and minutes per day). Scale: Not reported; Score: Not reported; Reliability: Not reported. *Self-efficacy for exercise (SEE):* Items: 9 (environmental climate, boredom, pain, exercising alone, pleasant or unpleasant exercise, being busy, tiredness, stress, and depression). Scale: 0 (no confidence) to 10 (high confidence); Score: 0–90 (Higher score indicates more self-efficacy for exercise); Reliability: Not reported. *Excess Benefits and Barriers Scale (EBBS):* 29 items to measure perceived benefits and barriers to PA (Benefits: improved life, physical performance, psychological outlook, social interaction, and preventive health. Barriers: exercise environment, time investment; physical effort; and family discouragement). Likert scale: Benefits score 1 (strongly disagree) to 4 (strongly agree); for barriers inverse score. Score: 43–172, higher values indicate greater perception of PA benefits; Reliability: Not reported.	**QoL:** *PHQ-9:* Total PHQ-9: *Mean* = 3.22 (*SD* = 4.8). No differences for depression according to exercise intensity ($F = 3.05$; $p = 0.53$). *SQoL:* Total: *Mean* = 19.3 (*SD* = 12.9). No differences for exercise intensity ($F = 0.40$; $p = 0.67$). *SPAS:* No differences for physical anxiety according to exercise intensity ($F = 1.97$; $p = 0.15$). **PA:** *IPAQ:* Inactive (*n* = 36; 42%), minimally active (*n* = 35; 41%), active (*n* = 15; 17%) participants. Differences favor to women (more active) than men ($p = 0.05$). *SEE:* Total score (*Mean* = 40.8; *SD* = 20.7) indicated moderate self-efficacy for exercise. Scores had significant effect for MET intensity ($F = 3.04$, $p < 0.001$). Mean score for inactive group (*n* = 34, *Mean* = 30.4) was significantly lower than for the minimally active group (*n* = 33; *Mean* = 46; $p = 0.03$) and the active group (*n* = 17; *Mean* = 49; $p = 0.01$). There was no difference between the minimally active and active groups ($p = 0.61$). *EBBS:* The greatest barriers to PA were physical effort, time, and accessibility. Scores were significantly lower in inactive participants compared to minimally active and active (not reported *p*-value) individuals. Individuals with higher total score (higher perceived benefits) were more likely to be active or minimally active than inactive. Individuals with a lower score (fewer perceived benefits) were more likely to be inactive than minimally active or active. No differences between the minimally active group and the active groups ($p = 0.90$).

Table 4. *Cont.*

Author (Year) Design	Sample Size (*N*) Type of Stoma PA [1]	Instruments	Statistical Data
Kindred et al. (2019) RCT [32]	*N* = 46 IG: *N* = 20 Male: *n* = 8; 40%; Female: *n* = 12; 60% CG: *N* = 26 Male: *n* = 12; 46.2%; Female: *n* = 14; 53.8% PA: Strength exercise; moderate intensity (12 weeks). *Submaximal fitness test:* Treadmill walking. Participants select the fastest steady pace walking one mile by estimating maximal oxygen consumption. *Accelerometer data:* Moderate to vigorous PA was measured with the Computer Science and Applications, Inc. monitor 3 consecutive days.	**PA:** *Body Esteem Scale (BES):* 35 Items into subscales according to the sex of the individual (Men: physical attractiveness, upper body strength and physical condition. Women: sexual attractiveness, weight concern and physical condition). 5-point Likert scale: 1 (very negative feelings) 5 (very positive feelings). Score: Higher indicates positive body esteem. Reliability: Not reported. *Body composition:* Measured by electrical impedance with a single frequency current (50 kHz) produced by a Quantum II RJL analyzer (RJL Systems, Clinton Township, MI).	*BES:* Significant associations on physical fitness (body esteem) in men (3 months: *b* = 0.68; *SD* = 0.35; *p* = 0.04; 6 months: *b* = 1.36; *SD* = 0.66; *p* = 0.04; and 12 months: *b* = 0.84; *SD* = 0.36; *p* = 0.03). No statistical difference in women. *Body composition:* Among women there were positive associations between reductions in body fat and body size (3 months: *b* = 3.71; *SD* = 1.79; *p* = 0.05; 12 months: *b* = 5.99; *SD* = 2.95; *p* = 0.05).
Russell (2017) Cross-sectional [33]	*N* = 2631 Male: 46%; Female: 54%. Type of stoma: Not Specified PA: Not reported	Instrument not reported. Ad hoc survey with open and closed questions using a 3 and 5-point Likert scale.	People declared QoL "a little worse" than before surgery (22.5% diagnosis/suspected hernia vs. 16% without hernia; $p < 0.05$). 32% with hernia declare being "much less active" than before surgery compared to 19% without hernia ($p < 0.001$).
Russell (2017) Cross-sectional [34]	*N* = 2631 Male: 46%; Female: 54%. Type of stoma: Not Specified PA: Not reported	Ad hoc *survey*: "Living with a stoma, your experience" with open and closed questions, rating scales of 3 and 5-points Likert scale.	People with stoma reported being less active (24.8%) compared to other conditions ($p < 0.001$). People who reported performing PA since intervention (38%) showed a higher perceived QoL ($p < 0.05$).
Krouse et al. (2017) Cross-sectional [35]	*N* = 1063 (target population) rectal cancer survivors (<5 years after diagnosis) during 2010–2011. *N* = 557 (sample) Type of stoma: Not specified PA: Not reported.	**QoL:** *City of Hope QoL Ostomy (COH-QoL-O)* (Ad hoc *questionnaire*): Items: Not specified. Scale: Not specified. Score: 0–10; higher score indicates better QoL. Subscales (physical, psychological, social, and spiritual well-being); Reliability: Not reported.	**QOL:** *COH-QoL-O:* Total QoL better in the group with guidelines with respect to not active (*Mean difference* = 0.43; 95% *CI*: 0.10–0.76). The group that followed the guidelines showed greater psychological well-being (*Mean difference* = 0.55; 95% *CI*: 0.23–0.88). Association between increased PA time and physical component (*Mean difference* = 6.0; 95% *CI*: 3.9–8.1), physical function (*Mean difference* = 7.0; 95% *CI*: 4.8–9.3), physical role (*Mean difference* = 4.5; 95% *CI*: 2.5–6.5), general health (*Mean difference* = 5.8; 95% *CI*: 3.5–8.2), vitality (*Mean difference* = 5.7; 95% *CI*: 3.6–7.8), social role (*Mean difference* = 3.7; 95% *CI*: 1.4–5.9) and emotional role (*Mean difference* = 3.8: 95% *CI*: 0.82–6.7). **PA:** *GLTEQ:* 34% (*n* = 190) not active, 26% (*n* = 145) insufficiently active, 13% (*n* = 72) meeting guidelines and 27% (*n* = 150) above guidelines. Relationship between PA time and being younger ($p < 0.001$), years since surgery ($p = 0.02$), college degree ($p < 0.001$), higher income ($p = 0.004$), married or partnered ($p = 0.003$), and comorbidity less than 2 ($p < 0.001$). No differences ($p = 0.08$) between having an ostomy and time of PA.

Table 4. *Cont.*

Author (Year) Design	Sample Size (*N*) Type of Stoma PA [1]	Instruments	Statistical Data
Courneya et al. (1999) Cohort [39]	*N* = 53 Males: 60%. Mean age: 60.7 years Type of stoma: Colostomy, ileostomy and urostomy. PA: Not reported.	**QoL:** *Functional Assessment of Cancer Therapy- Colorectal (FACT-C):* 6 dimensions: physical, functional, emotional, social, relationship with physician, additional aspects; Scale: Likert 0 (worst quality)–4 (best quality); Score: Not reported; Reliability: α = 0.85 (baseline); α = 0.91 (4 months). *Satisfaction with Life scale (SWL):* Items: 5 on unspecified aspects of life; Scale: Likert 1 (worst satisfaction)–7 (best satisfaction); Score: Not reported; Reliability: α = 0.91 (baseline); α = 0.92 (4 months). **PA:** *Godin Leisure Time Exercise Questionnaire (GLTEQ):* Items: 3 questions on frequency of days per week performing light, moderate, and strenuous exercise for 15 min. Scale: Open-ended.	**QoL:** *FACT-C:* Total: Baseline (*Mean* = 3.31; *SD* = 0.40). 4 months (*Mean* = 3.24; *SD* = 0.52). *Mean difference* = −0.07 (*SD* = 0.35). Physical: Baseline (*Mean* = 3.41; *SD* = 2.48). 4 months (*Mean* = 3.23; *SD* = 0.81). *Mean difference* = −0.18 (*SD* = 0.66). Functional: Baseline (*Mean* = 3.05; *SD* = 0.66). 4 months (*Mean* = 3.10; *SD* = 0.70). *Mean difference* = 0.05 (*SD* = 0.63). Emotional: Baseline (*Mean* = 3.37; *SD* = 0.60). 4 months (*Mean* = 3.49; *SD* = 0.50). *Mean difference* = −0.07 (*SD* = 0.35). Social: Baseline (*Mean* = 3.56; *SD* = 0.57). 4 months (*Mean* = 3.28; *SD* = 0.76). *Mean difference* = −0.28 (*SD* = 0.74). Changes in QoL at 4 months for social dimension ($p < 0.008$). *SWL:* Baseline (*Mean* = 4.98; *SD* = 1.51). 4 months (*Mean* = 5.00; *SD* = 1.41). *Mean difference* = 0.02 (*SD* = 1.12). Baseline correlation between satisfaction and functional dimension ($r = 0.70$). Multifactorial analysis indicated that functional dimension is the only one that explains 50% of variance: F (1.51) = 50.20; $p < 0.001$. Correlation at 4 months between satisfaction and functional ($r = 0.73$), emotional ($r = 0.56$), physical ($r = 0.54$), additional aspects ($r = 0.49$) and social ($r = 0.40$) dimensions. Multifactorial analysis: functional ($B = 0.58$), additional aspects ($B = 0.25$) and social ($B = 0.19$) dimensions explained 62% of variance: F (3.49) = 26.64; $p < 0.001$. Changes in satisfaction Baseline–4 months for physical ($r = 0.38$), functional ($r = 0.33$), and additional aspects ($r = 0.31$) explained 15% of variance: F (1.15) = 8.71; $p < 0.005$. **PA:** *GLTEQ:* Mild: Baseline (*Mean* = 2.64; *SD* = 2.48). 4 months (*Mean* = 2.75; *SD* = 2.52). *Mean difference* = 0.11 (*SD* = 2.77). Moderate: Baseline (*Mean* = 1.53; *SD* = 1.90). 4 months (*Mean* = 1.78; *SD* = 2.13). *Mean difference* = 0.25 (*SD* = 2.51). Extenuating: Baseline (*Mean* = 0.53; *SD* = 1.44). 4 months (*Mean* = 0.17; *SD* = 0.49). *Mean difference* = −0.36 (*SD* = 1.26). Increases in mild to moderate PA associated in total QoL at 4 months ($r = 0.39$; $p < 0.01$).

[1] PA: Physical Activity; [2] QoL: Quality of Life; [3] SD: Standard Deviation.

4. Discussion

Given the limited number of available studies, it is important to note that some exhibit low methodological rigor, such as the cross-sectional study by Russell [33,34], which received very low scores (25%). Other studies, such as those by Park et al. [26], Goodman et al. [27], Krogsgaard et al. [28], and Courneya et al. [39] are cross-sectional studies with secondary analyses of primary results, potentially representing redundant publications or a "salami slicing" strategy in scientific publishing [41]. Furthermore, the cohort study by Courneya et al. [39] was conducted over 20 years ago, and therefore does not account for recent advancements in this clinical field. Additionally, Wiskemann et al. [36] and Sica [37] presented case reports, while Isaacs [40] conducted a case series study. Isaacs' case series, published in 1984, also lacks more recent updates to validate its findings or incorporate newer, more sensitive analytical techniques. Of the included studies, only one was an experimental study [32] and another an analytical observational study [39], both of varying quality. The remaining studies include qualitative designs [30,38], which provide lower levels of evidence. Therefore, further research is needed to develop specific recommendations that promote healthy lifestyles incorporating PA, and to better understand its impact on the QoL for individuals with stomas.

In this context, the number of studies addressing the return to PA in patients with surgical stomas is scarce. In contrast, numerous publications have focused on aspects related to sexuality [42]. It has been noted that the experiences of individuals with stomas significantly affect their self-perception and behavior due to alterations in body image, lifestyle restrictions, and the need to overcome these challenges [43]. Individuals with stomas must learn to recognize and adapt to these changes, making behavioral adjustments to manage the associated restrictions. This process often involves deciding whether to disclose or conceal their stomas, based on concerns about social acceptance or potential rejection. This process involves optimizing internal resources and proactively seeking external support [13,35]. Thus, Mulchandani et al. [44] showed that PA interventions in the workplace have positive effects on metabolic and cardiovascular health, significantly reducing body weight (16 studies; *mean difference* = −2.61 kg, 95% *CI*: −3.89 to −1.33), body mass index (BMI) (19 studies; *mean difference* = $-0.42\ kg/m^2$, 95% *CI*: −0.69 to −0.15), and waist circumference (13 studies; *mean difference* = −1.92 cm, 95% *CI*: −3.25 to −0.60). Similarly, Reed et al. [45] found significant reductions in body weight (7 studies; *mean difference* = −0.83 kg; 95% *CI*: −1.64 to −0.02), BMI (6 studies; *mean difference* = $-0.35\ kg/m^2$; 95% *CI*: −0.62 to −0.07), low-density lipoprotein (4 studies; *mean difference* = −0.11 mmol/L; 95% *CI*: −0.17 to −0.04), and blood glucose (2 studies; *mean difference* = −0.18 mmol/L; 95% *CI*: −0.29 to −0.07). However, Mulchandani et al. [44] noted reductions in blood pressure, lipids, and blood glucose were not statistically significant.

From the perspective of professionals who care for individuals with stomas, describing and interpreting their personal awareness and associated behavioral choices is essential for offering practical, informational, and emotional support during the adaptation process [3,43]. This understanding helps professionals tailor their care to better address the unique challenges these individuals face.

Regarding the qualitative findings, the studies reviewed explored the experiences and perceptions of individuals with stomas. While these results are transferable to clinical practice, they are not generalizable due to the subjective nature of the data collected. Although these studies offer valuable insights into individual cases, their broader applicability is limited. Moreover, the lack of a clearly defined methodological framework in many of these studies' designs reduces the credibility of the findings. The evidence suggests that PA may influence QoL in stoma patients, though outcomes vary based on factors like the type of stoma. Thus, Saunders and Brunet [30] and Anderson et al. [38] identify several categories related to motivations, beliefs, barriers, social support, and perceived needs concerning PA and lifestyle in individuals with stomas, which impact the reduction in long-term complications. Both studies highlight the importance of understanding the motivations and perceived barriers related to engaging in PA and maintaining a healthy lifestyle,

as well as the need for practical guidance and support to help these individuals adopt healthier behaviors. Despite their shared focus, the studies differ in approach: Saunders and Brunet [30] emphasize individual's immediate experiences, while Anderson et al. [38] explore long-term expectations.

Secondly, the case studies also reveal the individual impact of PA and training programs on QoL, physical function, and psychosocial adaptation in individuals with stomas. Specifically, the cases presented by Wiskemann et al. [36] and Sica [37] highlight the return to PA in individuals with stomas following oncological treatments. In contrast, Isaacs [40] examines the effects of biochemical blood concentrations in athletes with stomas after high-intensity exercise. Collectively, these case studies underscore the importance of PA and supervised training programs in enhancing the adaptation and well-being of individuals with stomas. However, the findings are based on individual experiences and are not generalizable.

Finally, quantitative studies offer insights into the relationship between PA, QoL, and other factors in patients with stomas. According to Mo et al. [29] and Krouse et al. [35], active individuals report a better QoL compared to those who are inactive. Goodman et al. [27] categorize QoL into four profiles: good QoL, some problems with QoL, low QoL, and economic concerns. Lowe et al. [31], Kindred et al. [32], and Russell [33,34] do not provide specific information on QoL. Parastomal hernia, a common late complication after stoma formation, significantly decreases QoL and negatively affects body image and physical function [46,47]. Park et al. [26] found significant differences in QoL related to the presence of a hernia ($U = 11.99$; $p = 0.004$), with lower QoL observed in patients with parastomal hernias, as also noted by Krogsgaard et al. [28]. According to Haas et al. [48], parastomal hernia is a common complication following ostomy surgery, with an incidence rate of up to 78%. Most individuals develop a parastomal hernia within two years after surgery. Those with a parastomal hernia may experience pouch leakages, which can lead to skin damage and difficulties in maintaining a secure seal for the ostomy pouching system. They might also suffer from bowel obstructions and chronic pain in the abdomen, back, or hips. In rare cases, bowel strangulation and ischemia can occur. In addition to these complications, living with a parastomal hernia can significantly impact a person's QoL, contributing to stress related to body image, fatigue, and the physical burden of the hernia.

Evidence indicates that higher BMI, older age, female sex, larger stoma aperture, transperitoneal stoma creation, and greater waist circumference are risk factors for parastomal hernias [47]. Engaging in PA under professional supervision has been shown to provide beneficial physical effects for preventing parastomal hernias, as well as psychological benefits for patient recovery [49,50]. Thus, considering PA as an integral part of the care and treatment for stoma patients is crucial to minimize the risk of complications and enhance QoL. Additionally, PA may affect the patient's ability to adapt to and tolerate stoma [46,50], highlighting the importance of professional support and counseling [51–53].

The strengths of this study include the absence of prior reviews on this specific topic, enabling the identification of knowledge gaps related to the return to PA in stoma patients. Additionally, a critical appraisal was conducted based on the inclusion criteria, allowing for an evaluation of the quality of the available studies. However, the methodological limitations identified through the appraisal process pose challenges to the internal validity and reliability of the results. Despite these limitations, several studies were rated as high quality. In terms of review limitations, it is important to highlight that heterogeneity in study designs is a common limitation of scoping reviews, particularly on less-explored topics. Additionally, there is a potential for contextual bias since all the included studies were conducted in Europe, Canada, and the USA, where lifestyle and social norms related to PA may differ. Due to constraints on the length of the study, the critical appraisal process was not fully incorporated into the results section. Given the heterogeneity in study designs and evidence levels, the findings should be interpreted cautiously, considering the inherent limitations of the available data. Moving forward, more rigorous research designs, such as RCTs or longitudinal observational studies, are needed to enhance our understanding

of the relationship between surgical stomas and PA. Moreover, since most studies have focused on adults and oncology patients, future research should be extended to include children and non-oncology patients to achieve a more comprehensive understanding of this phenomenon.

5. Conclusions

The available evidence on the return to PA in individuals with surgical stomas within the context of post-surgery rehabilitation is limited and heterogeneous. While studies highlight concerns related to physical and psychological complications, as well as the importance of social support, counseling, and self-confidence in facilitating PA, there is a notable lack of rigorous, high-quality research. Most of the existing studies focus on adults and oncology patients, with few addressing children or non-oncology populations. Additionally, few studies provide robust evidence on the specific benefits and challenges of PA for QoL in this population. It is necessary to more clearly define the type, frequency, and intensity of exercise to ensure that the return to PA is both beneficial and free from stoma-related complications.

Further research, including RCTs and longitudinal studies, is needed to better understand the role of PA in improving the overall well-being of individuals with stomas. Future studies should focus on developing valid and reliable measurement tools and expanding research beyond the physical dimension to include psychological, emotional, and social factors. This will enable more comprehensive recommendations for PA in stoma patients, improving their QoL post-surgery.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/sports12100273/s1, Table S1: Search strategies; Table S2: Critical appraisal of the included studies; Table S3: Excluded studies.

Author Contributions: Conceptualization, A.-V.M.-J. and C.-A.R.-S.; methodology, A.-V.M.-J., C.-A.R.-S. and H.G.-d.l.T.; validation, A.-V.M.-J., C.-A.R.-S. and H.G.-d.l.T.; investigation, A.-V.M.-J.; resources, C.-A.R.-S. and H.G.-d.l.T.; data curation, A.-V.M.-J., C.-A.R.-S. and H.G.-d.l.T.; writing—original draft preparation, A.-V.M.-J.; writing—review and editing, A.-V.M.-J., C.-A.R.-S. and H.G.-d.l.T.; supervision, C.-A.R.-S. and H.G.-d.l.T.; project administration, A.-V.M.-J. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created.

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

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Article

Optimizing Motor Coordination in Children with Developmental Coordination Disorder: Mini-Handball vs. Motor Skills Training

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Abstract

Children with Developmental Coordination Disorder (DCD) experience motor competence challenges that hinder their participation in physical activities and affect daily functioning. While traditional motor skills training is commonly used, sport-based interventions offer the potential for greater benefits by providing dynamic, contextually rich environments for learning. This study aimed to evaluate the effectiveness of mini-handball training versus conventional motor skills training in improving coordination in children with DCD. Methods: Forty-four children aged 9–10 years from Khorezm, Uzbekistan, with coordination difficulties (scores below the 16th percentile in the MABC-2) were randomly assigned to three groups: mini-handball training (n = 15), motor skills training (n = 15), and control (n = 14). Both intervention groups participated in three 90 min sessions per week for 12 weeks. The mini-handball group engaged in sport-specific drills including passing, dribbling, shooting, and small-sided games, while the motor skills group performed balance, locomotor, and fine motor exercises. Pre- and post-intervention assessments were conducted using the MABC-2. Data were analyzed using linear mixed models with time, group, and their interaction as fixed effects. Results: Both intervention groups demonstrated significant improvements in motor coordination compared to controls. However, in general, the mini-handball group outperformed the other groups, particularly in domains requiring anticipatory control and visuomotor integration, including aiming and catching, balance, and overall coordination scores. Conclusions: Mini-handball represents a promising, ecologically valid intervention for children with DCD. By integrating motor skills practice with cognitive challenge, social interaction, and intrinsic motivation within a meaningful sport context, mini-handball appears more effective than traditional training approaches. These findings suggest that sport-based, open-skill interventions should be considered in therapeutic protocols, school curricula, and community programs for children with

DCD. Future research should examine long-term retention, transfer to daily activities, and implementation across diverse populations.

Keywords: developmental coordination disorder; motor skills training; mini-handball; MABC-2; sport-based intervention

1. Introduction

The neurodevelopmental disorder known as Developmental Coordination Disorder (DCD) is typified by notable deficiencies in the learning and application of coordinated motor skills. These deficits substantially hinder academic performance, everyday living activities, and general involvement [1], which, in turn, impacts children's general development and social integration [2]. Children with DCD typically present clumsiness, delayed acquisition of motor milestones, and poor fine and gross motor control, often manifesting as difficulties with handwriting, object manipulation, or balance during sports and play activities. These deficits frequently lead to reduced physical activity levels, lower self-perceived competence, and social withdrawal compared with their typically developing peers [3–5]. The identification and improvement of motor-based interventions to help children with DCD improve their motor competence and functional outcomes have received more attention recently. Numerous methods have been investigated. In children with DCD, gross motor-based interventions—such as organized physical activities, body function exercises, group games, and small-group formats—have continuously shown promise in boosting motor function, increasing physical fitness, and preventing obesity. Additional proof of these interventions' efficacy in enhancing gross motor function comes from a recent systematic review of research conducted between 2010 and 2022 [6].

Motor planning and predictive control issues are common in children with DCD, especially when it comes to tasks requiring a lot of time and space. Because they focus on the cognitive processes that underlie movement planning, interventions that use motor imagery and action observation have demonstrated promise in addressing these deficits [7].

Additionally, there is empirical support for cognitive-based interventions, particularly the Cognitive Orientation to Daily Occupational Performance (CO-OP) approach. This approach uses cognitive strategies to help children accomplish personally meaningful goals in daily activities, which improves their motor proficiency and occupational performance [7,8].

By utilizing peer interaction and motivating goal setting, group-based and goal-directed interventions have further proven their efficacy. These interventions, which usually combine motor learning principles, cognitive strategies, and structured practice schedules, are linked to notable enhancements in motor outcomes and participation in everyday activities [9].

The results of perceptual–motor interventions, which aim to improve the integration of sensory and motor processes, have been inconsistent. Although some research shows improvements in manual dexterity, balance, and object-control abilities like aiming and catching [10], other studies have not shown any appreciable progress [11].

Lastly, real-life tasks and targeted exercises are applied in activity-oriented and body function-oriented interventions to address specific motor deficits. These approaches have been shown to positively influence both motor function and skill acquisition [12,13]. A recent systematic review and meta-analysis of randomized controlled trials by Gao et al. [14] reported significant improvements in overall motor skills, balance, cognitive function, and activity performance following task-oriented interventions. Moreover, combining task- and process-

 https://doi.org/10.3390/sports14010001

oriented approaches has proven effective in enhancing general motor abilities in children with DCD.

Despite these various intervention options, there is limited evidence to help physical trainers, educators, and health professionals choose the most effective training approaches to improve physical fitness in children with poor motor coordination [15].

Recent research [16] has begun to investigate alternative intervention strategies that may provide broader benefits. Sports game interventions have shown promise in promoting the development of fundamental motor skills in children, implying that structured physical activities may offer a more engaging and contextually relevant approach to motor skills acquisition.

An example of this is mini-basketball, a sport that has proven effective in enhancing overall motor coordination in children with DCD [17]. Evidence indicates a close association between the development of complex motor skills and executive functions during childhood [18], implying that interventions integrating cognitively demanding activities may generate broader cognitive benefits. Within this context, mini-handball may be seen as a particularly promising modality for children with motor coordination difficulties. Previous studies highlight that mini-handball effectively promotes motor skills development, balance, and coordination [19], while its reliance on natural skills renders it accessible and easy to learn [20]. Furthermore, mini-handball is an inclusive adaptation of a team sport that encourages fair play, enjoyment, and physical literacy [21]. This perspective aligns with evidence showing that cognitively enriched physical activity, sports-based intervention models, and martial arts–based approaches produce meaningful improvements in balance, sensory integration, lower-limb strength, executive functioning, motivation, and overall motor proficiency in children with DCD, surpassing typical outcomes of standard physical education or non-adaptive motor practice [16,22–25]. Supporting this notion, a 12-week intervention study comparing open-skill (handball) and closed-skill (athletics) sports to a control group reported significant cognitive benefits associated with handball participation [26]. The dynamic demands of handball, requiring rapid decision-making, strategic planning, and motor adaptability, may, therefore, simultaneously foster motor and cognitive development [27].

Collectively, these findings highlight the importance of context-rich, cognitively engaging, and task-oriented intervention frameworks, as conventional fitness-based or repetitive practice approaches may be insufficient to drive neurofunctional and psychosocial adaptation [28].

However, empirical evidence directly comparing the effectiveness of mini-handball with traditional motor skills training in children with DCD is currently limited. Therefore, the present study aims to address this gap by conducting a comparative analysis of mini-handball and motor skills intervention programs in children with DCD, with the expectation—based on prior findings [17,28]—that mini-handball will lead to superior improvements in motor proficiency.

2. Methods

2.1. Participants

This study was conducted in Khorezm, Uzbekistan, with children aged 9–10 years. A group of 216 children (117 boys and 99 girls) was initially assessed using the Movement Assessment Battery for Children-Second Edition (MABC-2) tool to identify DCD. Based on the MABC-2 results, 129 children demonstrated scores below the 16th percentile, indicating coordination difficulties. Following the initial assessment, 85 children were excluded for several reasons. Children were not eligible if they presented with a diagnosed emotional, neurological, or movement disorder; a congenital, musculoskeletal, or cardiopulmonary condition that could influence postural control; intellectual impairment; current participation

https://doi.org/10.3390/sports14010001

in physical or occupational therapy; regular or intensive sports training; disruptive behavior during screening; or difficulty understanding and following task instructions. Therefore, 35 children lived too far from the training site, creating a high risk of irregular attendance as reported by their parents; 25 were excluded due to medical contraindications or a history of prior rehabilitation; 20 did not submit written informed consent because the parents declined long-term participation; and 5 were excluded to avoid gender imbalance, as an equal distribution between boys and girls was required across study groups. Accordingly, after applying all inclusion and exclusion criteria, a total of 44 children were deemed eligible for enrollment. Then, they were randomly assigned to three subgroups: a mini-handball group (15 children: 13 scored below 5th percentile and 2 scored between 5th and 16th percentile), a motor skills training program group (15 children: 12 scored below 5th percentile and 3 scored between 5th and 16th), and a control group (14 children: 13 scored below 5th percentile and 1 scored between 5th and 16th percentile).

2.2. Instruments and Measures

The primary assessment instrument employed in this study was the Movement Assessment Battery for Children–Second Edition (MABC-2), which was administered before and after the intervention to evaluate coordination performance. All assessments were conducted by an assessor blinded to participant group allocation. Participants were initially assessed using the MABC-2 prior to randomization and then reassessed by the same blinded assessor after twelve intervention sessions or the designated control period.

The MABC-2 is considered an appropriate tool for assessing the development of motor competencies in preschool children, with acceptable evidence supporting its validity and reliability for Age Band 1 [29]. Smits-Engelsman et al. [12] investigated the psychometric properties of the MABC-2 in a sample of 50 typically developing three-year-old children and concluded, based on test–retest analyses, that the instrument demonstrates a satisfactory level of reliability, even at this young age, and is sensitive to detecting individual changes. Similarly, Ellinoudis et al. [12], in a study involving 183 Greek children assessed with Age Band 1, reported that the MABC-2 is a valid and reliable measure for identifying motor difficulties in children aged 3 to 5 years. The test consists of eight tasks grouped into three subscales: Manual Dexterity (MD) evaluates fine motor control and hand–eye coordination through tasks such as placing pegs, threading beads, and drawing within boundaries; Aiming and Catching (A-C) assesses visual–motor integration and coordination of upper-limb movements using activities involving throwing toward and catching targets; Balance (BAL) measures static and dynamic balance through tasks such as standing on one leg, walking along a straight line, or balancing on a board. Raw scores are converted to standardized scores for each subscale and summed to yield a total standard score, which reflects overall motor proficiency. According to the test manual [30], the following cutoff points are recommended: scores below the 5th percentile indicate DCD; scores between the 6th and 15th percentile indicate risk of DCD (r-DCD); and scores above the 16th percentile are indicative of typical development (TD). To ensure consistency, all pre- and post-intervention assessments were administered by the same examiner and recorded on video for subsequent verification.

2.3. Procedures

Study Design

This study employed a pre-test–post-test experimental design, consisting of two experimental groups and one control group.

Each experimental group participated in structured training sessions designed to enhance coordination abilities and overall motor skills. The intervention lasted 12 weeks,

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during which participants attended three 90 min sessions per week. Sessions were tailored to each group, with the mini-handball and motor skills training groups engaging in targeted exercises, while the control group received conventional physical education lessons.

The handball activities integrated fundamental and specific skills, supporting exploratory behaviors, perceptual–motor interactions, and adaptive learning. The sport-specific drills—including passing, dribbling, shooting, and small-sided games—aimed at improving hand–eye coordination, agility, and reaction time. Its playful, social, and motivating nature can also boost children's intrinsic motivation and encourage lifelong physical activity habits, aligning with physical literacy goals. The training protocol was designed by a handball coach and organized into progressive stages: ball familiarization and grip; throwing; throwing and catching; combining throwing, catching, and movement; catching on the move; and dribbling.

The motor skills program included activities to develop manual dexterity, aiming and catching, and balance. Children manipulated small objects, threaded laces, and fastened buttons; caught and threw different balls; played bowling and reaction games; and practiced balance by walking on a line, picking up objects, responding to cues, and performing book-balancing tasks. The training protocol was designed by a trainer with a Ph.D. degree in the field of motor behavior and familiar with motor skills programs.

The control group continued to participate in their regular physical education classes as prescribed by the school curriculum, whereas only the two experimental groups were withdrawn from routine lessons and engaged in structured motor skills training sessions. The standard physical education classes consisted of general physical activities and traditional games, delivered in a broad, non-specialized format, without a specific focus on developing fundamental motor skills or sport-specific competencies.

All sessions were conducted by trained instructors following standardized protocols. Data were collected at baseline and post-intervention to evaluate the effectiveness of each program in improving coordination abilities, thereby allowing for comparative analysis across groups.

According to the Declaration of Helsinki, the research was approved by the Ethics Committee of Urgench State University (Code 12356).

2.4. Data Analysis

Descriptive statistics were calculated to describe all variables in this study. Four linear mixed models fit by maximum likelihood (one for each dimension and one for the total score of the MABC-2) were considered. According to Muth et al. [31] and Wiley and Rapp [32], linear mixed models are an adequate procedure for small sample designs. Time (pre-test, post-test) and groups (motor skills training, mini-handball, control) as well as their interaction were considered fixed effects. Subject-specific random intercepts were also considered to account for the repeated measurements. Assumptions were validated by analyzing the residuals graph. Following the guidelines of Meteyard and Davies [33], to decide between a model with only main effects and a model with main effects and interactions, for each dependent variable, nested models were considered and compared using Aikake Information Criterion (AIC), Bayesian Information Criterion (BIC), and Likelihood Ratio (LTR) tests. The main effects were firstly added to the model, and afterwards, the 2-way interaction was also considered. The model with the lowest AIC, the lowest BIC, and with a significant LTR test was selected. For each fixed effect, ANOVAs (analyses of variance) were then performed using Satterthwaite's method to detect significant effects. Whenever the interaction between main effects was statistically significant, multiple comparisons with Holm's correction and visual representations were considered.

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All statistical analyses were performed using R software (version 4.4.0), with packages lme4 (version 1.1-35.3), lmerTest (version 3.1-3), performance (version 0.15.0), multcomp (version 1.4-26), lsmeans (version 2.30-0), and ggplot2 (version 3.5.1). A significance level of 0.05 was considered.

3. Results

Table 1 presents the descriptive statistics for all dimensions and total score of the MABC-2 during both pre- and post-tests.

Table 1. Descriptive analysis of the MABC-2 during pre- and post-tests (n = 44).

Subscales	Pre-Test		Post-Test	
	M (SD)	Range	M (SD)	Range
Manual Dexterity	5.50 (1.41)	2–8	7.43 (2.08)	4–13
Aiming and Catching	6.93 (2.13)	1–11	8.50 (2.55)	3–14
Balance	5.20 (2.38)	1–10	8.00 (1.90)	4–12
Total Test Score	49.84 (7.19)	32–62	65.75 (9.78)	40–89

Notes: MABC-2 = Movement Assessment Battery for Children-Second Edition.

According to Table 1, the present sample presented higher scores in the post-test for all variables.

To analyze the significance of these differences and the influence of groups (motor skills training, mini-handball, control) in these results, linear mixed models were considered.

Table 2 presents the linear mixed model selection for each of the variables in Table 1. Main fixed effects were first added to the model. Afterwards, the two-way interaction was also added. At each step, the model was compared to the previous one. The model with the lowest AIC, the lowest BIC, and with a significant LTR test was selected.

Table 2. Model selection for each dependent variable (n = 44).

Dependent Variable	Model Name	Nested/Simpler Model	Fixed Effects Added	Random Effects	Model Fit		LRT Test Against Nested	
				Subjects	AIC	BIC	df	χ^2
Manual Dexterity	Null	-	-	Intercepts	378.2	385.6		
	Main effects	Null	Time + Groups	Intercepts	353.9	368.8	3	30.26 ***
	2-way interaction	Main effects	Time × Groups	Intercepts	348.9	368.7	2	9.08 *
Aiming and Catching	Null	-	-	Intercepts	413.4	420.8		
	Main effects	Null	Time + Groups	Intercepts	398.1	412.9	3	21.31 ***
	2-way interaction	Main effects	Time × Groups	Intercepts	390.4	410.3	2	11.64 **
Balance	Null	-	-	Intercepts	420.3	427.7		
	Main effects	Null	Time + Groups	Intercepts	388.2	403.1	3	38.12 ***
	2-way interaction	Main effects	Time × Groups	Intercepts	381.9	401.7	2	10.29 **
Total Test Score	Null	-	-	Intercepts	687.6	695.0		
	Main effects	Null	Time + Groups	Intercepts	615.2	630.0	3	78.44 ***
	2-way interaction	Main effects	Time × Groups	Intercepts	596.5	616.3	2	22.71 ***

Notes: Time: 1—Pre-test, 2—Post-test; Groups: 1—Motor skills training (n = 15), 2—Mini-handball (n = 15), 3—Control group (n = 14); AIC = Aikake Information Criterion; BIC = Bayesian Information Criterion; LRT = Likelihood Ratio Test; * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

https://doi.org/10.3390/sports14010001

As can be seen in Table 2, according to AIC, BIC, and the LTR test, the model with the main effects and the two-way interaction as fixed effects is the one with the best performance for all dependent variables and will be the one considered in the following analyses.

3.1. Manual Dexterity

Table 3 presents the results of the linear mixed model, namely, the effect of each independent variable, with the results from ANOVAs performed using Satterthwaite's method.

Table 3. Linear mixed model results for manual dexterity.

	Manual Dexterity		
Fixed Effects	**F**	**df1; df2**	***p***
Time	42.89	1; 44	<0.001
Groups	2.05	2; 44	0.141
Time × Groups	5.04	2; 44	0.011
Random Effects (subject—intercept)			
Variance		1.86	
SD		1.36	
$N_{subjects}$		44	
Observations		88	
Marginal R^2/Conditional R^2		0.329/0.540	

Notes: Time: 1—Pre-test, 2—Post-test; Groups: 1—Motor skills training (n = 15), 2—Mini-handball (n = 15), 3—Control group (n = 14); p-values for fixed effects calculated using Satterthwaite's approximations.

According to Table 3, only time and the interaction between time and groups had a statistically significant effect on manual dexterity. As can be confirmed by analyzing Figure 1 and the significance of the multiple comparisons (with Holm's correction; Table 4), in the pre-test, the scores of all groups were similar, but the scores in the post-test were always higher than those in the pre-test for all groups. However, in the control group, those differences between scores in the pre-test and post-test were not statistically significant.

Table 4. Multiple comparisons for significant interactions when the dependent variable is manual dexterity (n = 44).

Difference	**Estimate**	**SE**	**t**	***p***
Time1 Groups1—Time2 Groups1	−2.20	0.50	−4.42	<0.001
Time1 Groups1—Time1 Groups2	−0.20	0.60	−0.33	1.00
Time1 Groups1—Time2 Groups2	−3.07	060	−5.10	<0.001
Time1 Groups1—Time1 Groups3	−0.31	0.61	−0.51	1.00
Time1 Groups1—Time2 Groups3	−0.95	0.61	−1.56	0.865
Time2 Groups1—Time1 Groups2	2.00	0.60	3.33	0.013
Time2 Groups1—Time2 Groups2	−0.87	0.60	−1.44	0.920
Time2 Groups1—Time1 Groups3	1.89	0.61	3.09	0.025
Time2 Groups1—Time2 Groups3	1.25	0.61	2.04	0.358
Time1 Groups2—Time2 Groups2	−2.87	0.50	−5.76	<0.001
Time1 Groups2—Time1 Groups3	−0.11	0.61	−0.18	1.000
Time1 Groups2—Time2 Groups3	−0.75	0.61	−1.23	1.000
Time2 Groups2—Time1 Groups3	2.76	0.61	4.51	<0.001
Time2 Groups2—Time2 Groups3	2.11	0.61	3.46	0.010
Time1 Groups3—Time2 Groups3	−0.64	0.52	−1.25	1.000

Notes: Time: 1—Pre-test, 2—Post-test; Groups: 1—Motor skills training (n = 15), 2—Mini-handball (n = 15), 3—Control group (n = 14); Holm's correction for multiple comparisons was used.

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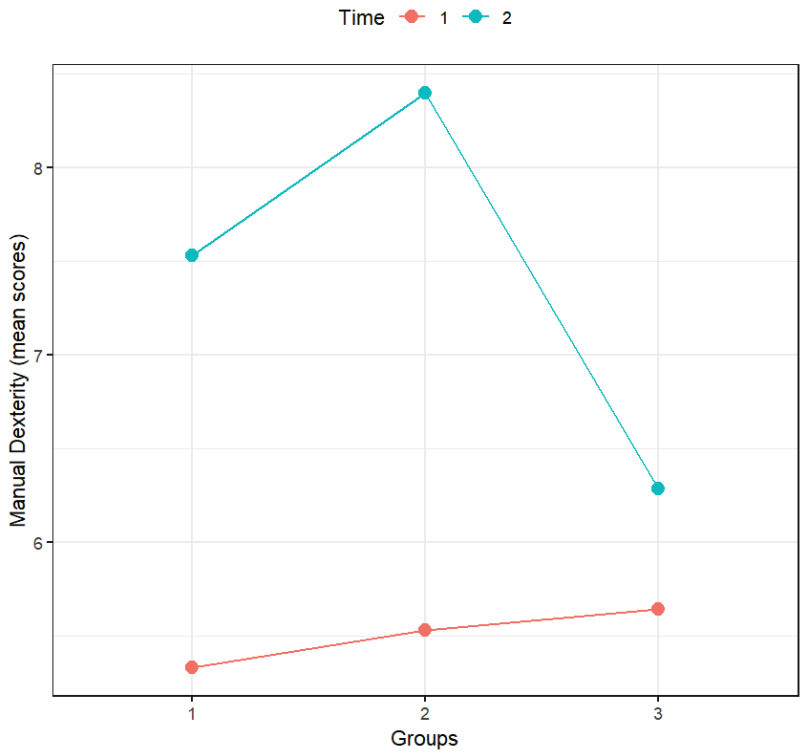


Figure 1. Effect of the interaction between groups and time on manual dexterity (n = 44). Notes: Time: 1—Pre-test, 2—Post-test; Groups: 1—Motor skills training (n = 15), 2—Mini-handball (n = 15), 3—Control group (n = 14).

When comparing the groups, the only statistically significant differences were the post-test difference between the mini-handball group and the control group, the change in scores from pre- to post-test in the motor skills training group, and the change in scores from pre- to post-test in the mini-handball group.

3.2. Aiming and Catching

Table 5 presents the results for the linear mixed model, namely, the effect of each independent variable, with the results from ANOVAs performed using Satterthwaite's method.

Table 5. Linear mixed model results for aiming and catching.

	Aiming and Catching		
Fixed Effects	**F**	**df1; df2**	***p***
Time	12.37	1; 88	<0.001
Groups	7.20	2; 88	0.001
Time × Groups	6.22	2; 88	0.003
Random Effects (subject—intercept)			
Variance		4.13	
SD		2.03	
$N_{subjects}$		44	
Observations		88	
Marginal R^2/Conditional R^2		0.315/0.315	

Notes: Time: 1—Pre-test, 2—Post-test; Groups: 1—Motor skills training (n = 15), 2—Mini-handball (n = 15), 3—Control group (n = 14); p-values for fixed effects calculated using Satterthwaite's approximations.

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According to Table 5, time, groups, and the interaction between time and groups had a statistically significant effect on aiming and catching. As can be confirmed by analyzing Figure 2 and the significance of the multiple comparisons (with Holm's correction; Table 6), in the pre-test, the scores of all groups were similar, and the scores in the post-test were higher than those in the pre-test for the motor skills training group and mini-handball group but only significantly higher for the mini-handball group. The differences between pre- and post-tests for the control group were not statistically significant.

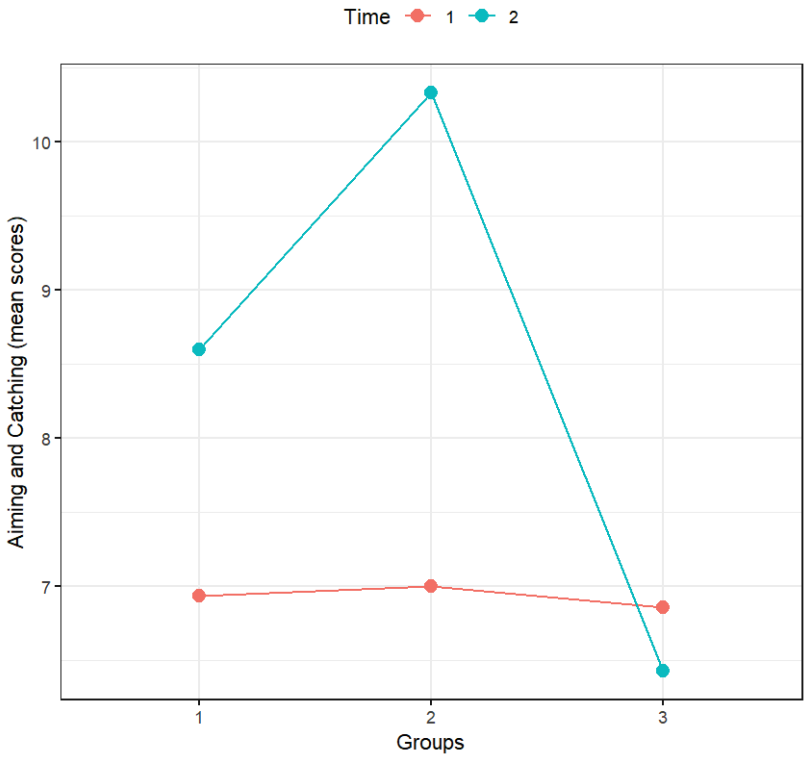


Figure 2. Effect of the interaction between groups and time on aiming and catching (n = 44). Notes: Time: 1—Pre-test, 2—Post-test; Groups: 1—Motor skills training (n = 15), 2—Mini-handball (n = 15), 3—Control group (n = 14).

The interaction between time and groups was statistically significant. When comparing groups, the only statistically significant differences were the differences between the mini-handball group and the control group in the post-test as well as the difference in the mini-handball group scores between the pre- and post-test.

Table 6. Multiple comparisons for significant interactions when the dependent variable is aiming and catching (n = 44).

Difference	Estimate	SE	t	*p*
Time1 Groups1—Time2 Groups1	−1.67	0.74	−2.25	0.218
Time1 Groups1—Time1 Groups2	−0.07	0.74	−0.09	1.000
Time1 Groups1—Time2 Groups2	−3.40	0.74	−4.58	<0.001
Time1 Groups1—Time1 Groups3	0.08	0.75	0.10	1.000
Time1 Groups1—Time2 Groups3	0.50	0.75	0.67	1.000
Time2 Groups1—Time1 Groups2	1.60	0.74	2.16	0.237
Time2 Groups1—Time2 Groups2	−1.73	0.74	−2.34	0.218
Time2 Groups1—Time1 Groups3	1.74	0.75	2.31	0.218
Time2 Groups1—Time2 Groups3	2.17	0.75	2.88	0.056

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Table 6. *Cont.*

Difference	Estimate	SE	t	*p*
Time1 Groups2—Time2 Groups2	−3.33	0.74	−4.50	<0.001
Time1 Groups2—Time1 Groups3	0.14	0.75	0.19	1.000
Time1 Groups2—Time2 Groups3	0.57	0.75	0.76	1.000
Time2 Groups2—Time1 Groups3	3.48	0.75	4.61	<0.001
Time2 Groups2—Time2 Groups3	3.90	0.75	5.17	<0.001
Time1 Groups3—Time2 Groups3	0.43	0.77	0.56	1.000

Notes: Time: 1—Pre-test, 2—Post-test; Groups: 1—Motor skills training (n = 15), 2—Mini-handball (n = 15), 3—Control group (n = 14); Holm's correction for multiple comparisons was used.

3.3. Balance

Table 7 presents the results for the linear mixed model, namely, the effect of each independent variable, with the results from ANOVAs performed using Satterthwaite's method.

Table 7. Linear mixed model results for balance.

	Balance		
Fixed Effects	**F**	**df1; df2**	***p***
Time	56.93	1; 44	<0.001
Groups	2.82	2; 44	0.070
Time × Groups	5.79	2; 44	0.006
Random Effects (subject—intercept)			
Variance		2.98	
SD		1.73	
$N_{subjects}$		44	
Observations		88	
Marginal R^2/Conditional R^2		0.411/0.543	

Notes: Time: 1—Pre-test, 2—Post-test; Groups: 1—Motor skills training (n = 15), 2—Mini-handball (n = 15), 3—Control group (n = 14); p-values for fixed effects calculated using Satterthwaite's approximations.

According to Table 7, only time and the interaction between time and groups had a statistically significant effect on balance. As can be confirmed by analyzing Figure 3 and the significance of the multiple comparisons (with Holm's correction; Table 8), in the pre-test, the scores of all groups were similar, and the scores in the post-test were always significantly higher than those in the pre-test for all groups. However, the difference between pre- and post-test scores was more accentuated for the mini-handball group.

Table 8. Multiple comparisons for significant interactions when the dependent variable is balance (n = 44).

Difference	Estimate	SE	t	*p*
Time1 Groups1—Time2 Groups1	−1.80	0.63	−2.86	0.044
Time1 Groups1—Time1 Groups2	0.87	0.72	1.21	0.797
Time1 Groups1—Time2 Groups2	−3.67	0.72	−5.12	<0.001
Time1 Groups1—Time1 Groups3	0.94	0.73	1.29	0.797
Time1 Groups1—Time2 Groups3	−1.06	0.73	−1.45	0.753
Time2 Groups1—Time1 Groups2	2.67	0.72	3.73	0.004
Time2 Groups1—Time2 Groups2	−1.87	0.72	−2.61	0.069
Time2 Groups1—Time1 Groups3	2.74	0.73	3.77	0.004
Time2 Groups1—Time2 Groups3	0.74	0.73	1.02	0.797

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Table 8. *Cont.*

Difference	Estimate	SE	t	*p*
Time1 Groups2—Time2 Groups2	−4.53	0.63	−7.19	<0.001
Time1 Groups2—Time1 Groups3	−0.08	0.73	−0.11	0.917
Time1 Groups2—Time2 Groups3	−1.92	0.73	−2.64	0.069
Time2 Groups2—Time1 Groups3	4.61	0.73	6.33	<0.001
Time2 Groups2—Time2 Groups3	2.61	0.73	3.58	0.006
Time1 Groups3—Time2 Groups3	−2.00	0.65	−3.07	0.027

Notes: Time: 1—Pre-test, 2—Post-test; Groups: 1—Motor skills training (n = 15), 2—Mini-handball (n = 15), 3—Control group (n = 14); Holm's correction for multiple comparisons was used.

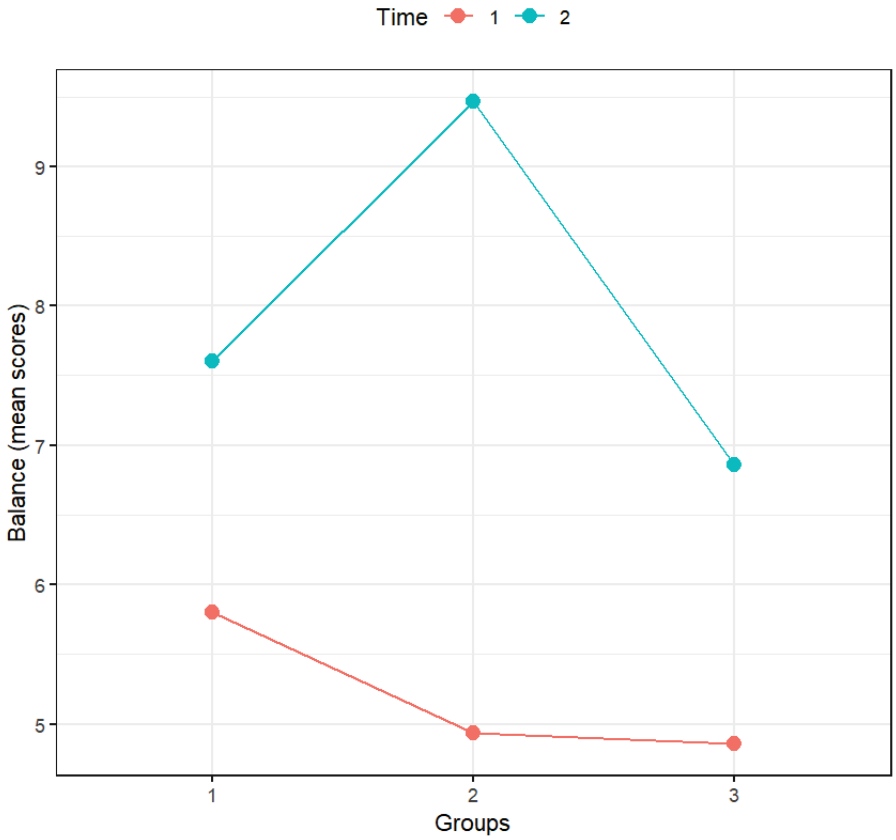


Figure 3. Effect of the interaction between groups and time on balance (n = 44). Notes: Time: 1—Pre-test, 2—Post-test; Groups: 1—Motor skills training (n = 15), 2—Mini-handball (n = 15), 3—Control group (n = 14).

The interaction between time and groups was statistically significant. When comparing groups, the only statistically significant differences were the differences between the mini-handball group and the control group in the post-test, the difference in the motor skills training group scores between the pre- and post-test, the difference in the mini-handball group scores between the pre- and post-test, and also the difference in the control group scores between the pre- and post-test.

3.4. Total Test Score

Table 9 presents the results for the linear mixed model, namely, the effect of each independent variable, with the results from ANOVAs performed using Satterthwaite's method.

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Table 9. Linear mixed model results for total test score.

	Total Test Score		
Fixed Effects	**F**	**df1; df2**	***p***
Time	147.22	1; 44	<0.001
Groups	14.64	2; 44	<0.001
Time × Groups	14.46	2; 44	<0.001
Random Effects (subject—intercept)			
Variance		36.95	
SD		6.08	
$N_{subject}$		44	
Observations		88	
Marginal R^2/Conditional R^2		0.682/0.729	

Notes: Time: 1—Pre-test, 2—Post-test; Groups: 1—Motor skills training (n = 15), 2—Mini-handball (n = 15), 3—Control group (n = 14); p-values for fixed effects calculated using Satterthwaite's approximations.

According to Table 9, time, groups, and the interaction between time and groups had a statistically significant effect on total test score. As can be confirmed by analyzing Figure 4 and the significance of the multiple comparisons (with Holm's correction; Table 10), in the pre-test, the scores of all groups were similar, and the scores in the post-test were always significantly higher than those in the pre-test for all groups. However, the difference between pre- and post-test scores was more accentuated for the mini-handball group and less accentuated for the control group.

Table 10. Multiple comparisons for significant interactions when the dependent variable is total test score (n = 44).

Difference	**Estimate**	**SE**	**t**	***p***
Time1 Groups1—Time2 Groups1	−14.27	2.22	−6.43	<0.001
Time1 Groups1—Time1 Groups2	0.60	2.40	0.25	1.000
Time1 Groups1—Time2 Groups2	−24.33	2.40	−10.12	<0.001
Time1 Groups1—Time1 Groups3	2.16	2.45	0.88	1.000
Time1 Groups1—Time2 Groups3	−5.84	2.45	−2.39	0.077
Time2 Groups1—Time1 Groups2	14.87	2.40	6.18	<0.001
Time2 Groups1—Time2 Groups2	−10.07	2.40	−4.19	<0.001
Time2 Groups1—Time1 Groups3	16.43	2.45	6.72	<0.001
Time2 Groups1—Time2 Groups3	8.43	2.45	3.45	0.006
Time1 Groups2—Time2 Groups2	−24.93	2.22	−11.23	<0.001
Time1 Groups2—Time1 Groups3	1.56	2.45	0.64	1.000
Time1 Groups2—Time2 Groups3	−6.44	2.45	−2.64	0.051
Time2 Groups2—Time1 Groups3	26.50	2.45	10.83	<0.001
Time2 Groups2—Time2 Groups3	18.50	2.45	7.56	<0.001
Time1 Groups3—Time2 Groups3	−8.00	2.30	−3.48	0.006

Notes: Time: 1—Pre-test, 2—Post-test; Groups: 1—Motor skills training (n = 15), 2—Mini-handball (n = 15), 3—Control group (n = 14); Holm's correction for multiple comparisons was used.

The interaction between time and groups was statistically significant. When comparing groups, there were statistically significant differences between all groups in the post-test and also when comparing each group's scores between the pre- and post-test.

https://doi.org/10.3390/sports14010001

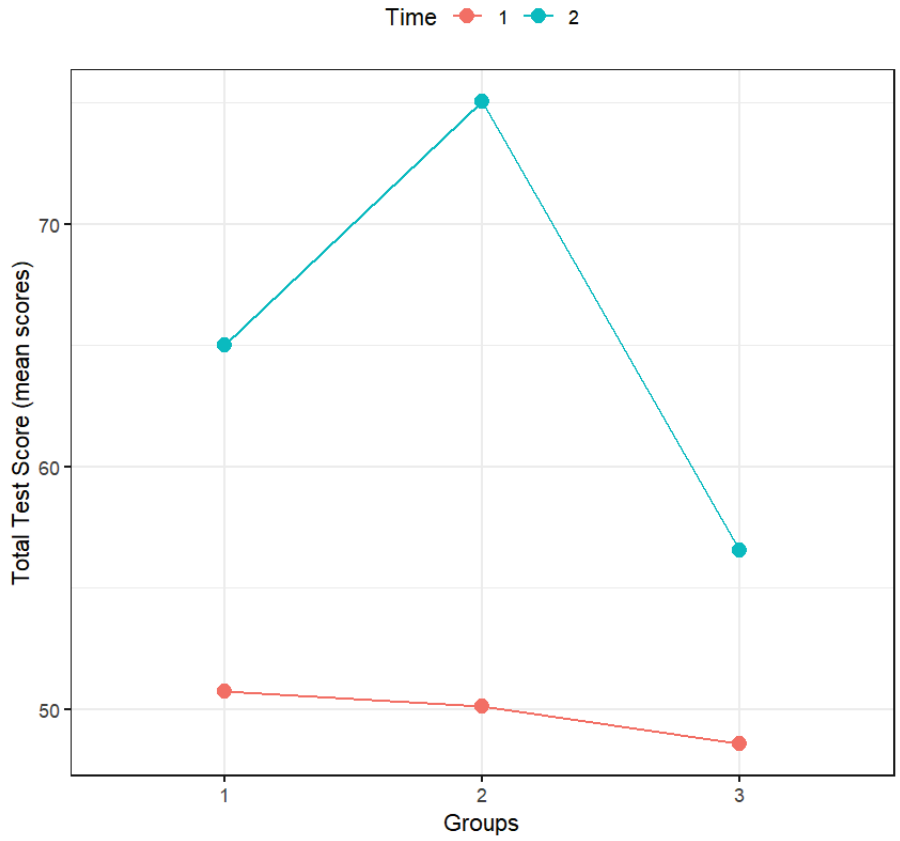


Figure 4. Effect of the interaction between groups and time on total test score (n = 44). Notes: Time: 1—Pre-test, 2—Post-test; Groups: 1—Motor skills training (n = 15), 2—Mini-handball (n = 15), 3—Control group (n = 14).

4. Discussion

The present study examined the comparative effects of mini-handball and traditional motor skills training on the coordination abilities of children with DCD. The findings suggest that mini-handball constitutes a highly effective approach for children with DCD, producing greater overall gains in the total test score than both conventional motor skills training and the control condition. These outcomes support the authors' initial expectation that mini-handball would yield more substantial enhancements in motor competence. Concerning the three dimensions of the MABC-2 (manual dexterity, aiming and catching, and balance), both interventions (motor skills training and mini-handball) produced significant improvements in motor competence, while the control group showed minimal changes. Specifically, concerning manual dexterity, our results showed significant improvements for the motor skills training and mini-handball groups but not for the control group. Moreover, there were significant differences between the mini-handball and control groups, and the interaction between time and groups was significant. For aiming and catching, significant improvements were observed only in the mini-handball group, while no significant changes occurred in the motor skills training or control groups. Significant differences were also found between the mini-handball and control groups, and the interaction between time and groups was significant. Regarding balance, all three groups—motor skills training, mini-handball, and control—showed significant differences over time. There were also significant differences between the mini-handball and control groups, and the interaction between time and groups was significant. Finally, for the total score, significant differences were found across all groups. Significant differences were identified between every pair

https://doi.org/10.3390/sports14010001

of groups (motor skills training vs. mini-handball, motor skills training vs. control, and mini-handball vs. control), and the interaction between time and groups was significant. For all the variables of the MABC-2 (manual dexterity, aiming and catching, balance, and total score), the interaction between time and group was significant. These findings highlight the potential of sport-based interventions, particularly mini-handball, as effective modalities for fostering motor development in children with DCD.

The present findings are consistent with prior research highlighting the efficacy of gross motor-based and structured activity interventions in improving motor proficiency and physical fitness among children with motor coordination difficulties [6,12]. However, the current study extends this body of literature by demonstrating that an open-skill, sport-based activity such as mini-handball may offer more pronounced benefits compared to traditional, closed-skill training approaches. These results corroborate those of Zolghadr et al. [17], who indicate that mini-basketball training has a greater positive impact on the overall motor coordination of children with DCD compared to general physical education programs. Identical results were found in a previous study from Tsai et al. [34], who examined the potential effects of a 10-week soccer training program on inhibitory control and neuroelectric functioning in children diagnosed with DCD and in typically developing children. Pre- and post-intervention assessments involved a visuospatial attention orienting task performed with the lower extremities, while concurrent recordings of event-related potentials were obtained. Following the intervention, the DCD-training group exhibited notable improvements in inhibitory control and a reduction in latency response. Overall, these findings suggest that participation in soccer training yields measurable benefits in both neuroelectric indices and behavioral performance for children with DCD. However, Hung and Pang [35], in a randomized controlled pilot intervention study, verified that group-based training produced similar gains in motor performance compared to individual-based training when studying 8 year-old children with DCD. In a very recent study, Valadi et al. [36] adopted an ecological approach, investigated the effectiveness of non-linear pedagogy interventions based on the constraint-led approach for both fundamental movement skills and selected handball sports skills, and evaluated their impact on typical children's physical literacy and quality of life. The study demonstrated that both constraint-led approach protocols (non-linear fundamental movement skills and non-linear handball sports skills) effectively improved physical literacy and quality of life in children aged 8–10 years. The authors observed that enhancing physical literacy led to a better quality of life, with the non-linear fundamental movement skills protocol producing greater improvements. These findings highlight that applying ecological dynamics principles through non-linear pedagogy and affordance-rich environments can promote physical literacy and support long-term well-being in children. These findings reveal a trend opposite to that observed in our study, as the group that received the fundamental motor skills intervention demonstrated greater improvement in motor literacy compared to the group that participated in the handball-based intervention. However, it is important to note that the children in that study did not present DCD. A plausible explanation for this discrepancy may lie precisely in the profile of children with DCD. Their reduced participation in physical activity, diminished self-perceived competence, and increased social disengagement can be reversed in sport contexts, as sport activities tend to be more stimulating and can, therefore, enhance motivation and engagement—both of which are essential for acquiring specific and meaningful skills. The peer interaction fostered by sport activities, along with the enjoyment derived from game participation, appears to be particularly beneficial for children with DCD.

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Regarding the absence of significant differences between the mini-handball group and motor skills training group in the dimensions of the MABC-2 (manual dexterity, aiming and catching, and balance), a plausible explanation is the possible overlap in the motor demands inherent to both interventions. Despite differing in format, the two programs may have targeted largely similar underlying abilities, including hand–eye coordination, balance, object manipulation, and postural control. Consequently, the sport-specific context of mini-handball may not have conferred an additional advantage of sufficient magnitude to be reflected in the MABC-2 subscale scores. Another reason may be contributed to the absence of differences between the two groups. Although the duration and intensity of the intervention may have been adequate to elicit within-group gains, they may have been insufficient to produce distinct differences between the groups. A 12-week program delivered three times per week typically supports measurable pre–post progress; however, such a timeframe may not allow one intervention modality to yield substantially greater improvements than the other. If both groups were subjected to a higher number of sessions, the accumulated volume of practice could generate statistically significant differences between the groups.

However, as mentioned above, in the total MABC-2 test score, the mini-handball group stood out significantly from the other two groups. This result is consistent with research emphasizing the role of open-skill sports in stimulating not only motor learning but also higher-order cognitive processes, such as executive function, decision-making, and attentional control [18,26]. The dynamic, unpredictable, and socially interactive nature of mini-handball appears to provide children with repeated opportunities to engage in rapid motor planning, spatial–temporal adjustments, and flexible coordination strategies—mechanisms that may explain its superior effects. Considering the results and arguments presented, our results confirm the initial hypothesis that a mini-handball-oriented intervention leads to better improvements in motor proficiency.

Another important contribution of this study concerns the motivational and ecological dimensions of mini-handball. Unlike conventional motor drills, which may be perceived as repetitive and less engaging, mini-handball integrates skill development within a meaningful, enjoyable, and socially interactive context. Enjoyment and peer interaction are key determinants of adherence, particularly in pediatric populations, and may partly explain the greater efficacy observed in this group. This finding resonates with the concept of physical literacy, which emphasizes lifelong engagement in physical activity through the development of competence, confidence, and motivation [21]. By fostering both motor competence and intrinsic motivation, mini-handball may promote sustainable engagement in physical activity beyond the intervention period, addressing one of the persistent challenges in DCD management. Mini-handball is a sport that really improves motor coordination, driving motor learning and motor transfer according to the ecological dynamics idea. Across the variations in the task and the environmental constraints (field size, rules, number of players), children explore solutions in context and interact with each other, challenging themselves. This supports perception–action coupling and better generalization and transfer to activities of daily living, play activities, physical education, and a variety of sports. General motor skills practice can still be important to surpass DCD [37,38], but collective sports give children with DCD the motivation, skill adaptability, and social participation opportunities that general skills alone cannot provide.

The findings also carry important implications for practice. For physical trainers, educators, and health professionals, the evidence suggests that integrating sport-based activities such as mini-handball into school curricula, community programs, or therapeutic protocols may provide an effective, inclusive, and engaging strategy to support children

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with DCD. Moreover, the comparative analysis highlights the need to move beyond traditional therapeutic models, considering ecologically valid interventions that align more closely with children's real-world experiences and social environments.

Despite these promising results, several limitations should be acknowledged. The sample size, while adequate to perform the considered analyses, remains modest and limits generalizability. Although it was sufficient to detect several significant group differences, there is the potential for type II errors, and non-significant findings should be carefully interpreted. The intervention duration of 12 weeks, although sufficient to produce measurable changes, does not allow conclusions about long-term retention or transfer of skills to everyday contexts. Furthermore, reliance on the MABC-2 as the sole outcome measure restricts the scope of evaluation to motor coordination without capturing potential gains in executive function, psychosocial participation, or quality of life. Future research should, therefore, adopt a more multidimensional assessment framework, incorporating cognitive, emotional, and social outcomes as well as longitudinal follow-up designs to determine the sustainability of intervention effects. Additionally, comparative studies across different cultural, educational, and socioeconomic contexts are essential to evaluate the adaptability and scalability of mini-handball interventions.

5. Conclusions

The results obtained indicate that mini-handball is a particularly effective intervention for children with DCD, demonstrating superior effects in the total test score compared to traditional motor skills training and the control group. The authors confirmed the initial hypothesis that mini-handball will lead to superior improvements in motor proficiency. Although both intervention programs—mini-handball and motor skills training—fostered progress in motor competencies, mini-handball, in general, showed greater efficacy. The control group exhibited no relevant changes over the study period. Given the evidence presented, the authors suggest that interventions based on open-skill sports, such as mini-handball, should be incorporated into therapeutic protocols, community programs, and school curricula for children with DCD, as they represent more effective and meaningful alternatives to approaches centered solely on traditional motor exercises.

Author Contributions: Conceptualization, H.B. and O.S.; methodology, P.R. and R.B.; software, C.S.; validation, P.R. and R.B.; formal analysis, C.S.; investigation, O.S. and J.J.; resources, H.B. and S.G.; data curation, P.R. and C.S.; writing—original draft preparation, O.S. and T.S.; writing—review and editing, P.R. and R.B.; visualization, O.V. and R.B.; supervision, P.R. and R.B.; project administration, O.S. and R.Q. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: This study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Ethics Committee of Mamun University.

Informed Consent Statement: Informed consent was obtained from all parents or legal guardians of the children who participated in this study.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Acknowledgments: We sincerely thank the administration of Mamun University, especially Arslonbek Otanazarovich Nurjonov, for creating favorable conditions to conduct our research.

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

https://doi.org/10.3390/sports14010001

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https://doi.org/10.3390/sports14010001

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The Role of Sports in Building Resilience: A Machine Learning Approach to the Psychological Effects of the COVID-19 Pandemic on Children and Adolescents

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Abstract: (1) Background: This study evaluated whether physical activity and sports serve as a protective factor in mitigating COVID-19 pandemic long-term consequences. (2) Methods: A survey of 1702 participants (8–18 years) used the Impact of Event Scale (IES), Generalized Anxiety Disorder Scale (GAD-7), and Center for Epidemiological Studies Depression Scale for Children (CES-DC). Participants were categorized based on their engagement in sports, cultural activities, or sedentary behaviors. Statistical analysis included non-parametric tests, CHAID models, and clustering. (3) Results: In total, 65.5% of participants experienced minimal to mild anxiety, and 34.5% reported moderate to severe anxiety. The main predictor of depression is the sample age, followed by the training experience. Depressive symptoms were identified in 71.3% of participants (75.7% adolescents; 64% children). Adolescents with longer training experience (67.6%) showed lower depression compared to those with shorter experience (77.2%). For post-traumatic stress, 38% of children and 46% of adolescents exceeded cut-off scores for significant symptoms, with age and training level identified as key predictors. Among children, sport experience with low weekly frequency was associated with the lowest depression rates (59.5%). (4) Conclusions: Four years after the pandemic, a high percentage of anxiety and depression disorders is observed in the youth population, particularly among adolescents. Sports appear to slightly alleviate this serious condition.

Keywords: pandemic; COVID-19; sports; psychological distress; adaptation process; anxiety; depression; resilience; adolescent; child; surveys and questionnaires

1. Introduction

Four years after its onset, the COVID-19 pandemic continues to raise significant concerns about the long-term consequences of the disease, leading the scientific community to investigate the complexities of the post-COVID clinical landscape. A great number of studies have revealed persistent symptoms extending beyond acute manifestations [1,2]. Among these, anxiety and depression emerge as significant issues requiring a thorough understanding and effective

management strategies [3]. The current focus is now directed towards understanding the persistence of these effects among children and adolescents, addressing their specific needs [4,5].

Engagement in activities that stimulate children's commitment and skills helps in overcoming these issues, especially when performed in groups and properly guided by a skilled operator. By cultural activities, we mean workshop, theatrical, and musical activities. Physical and sport activities have been recognized as a key element in promoting overall health and well-being, and psychological resilience in mitigating post-COVID psychological symptoms [6]. Sport performance is associated with self-esteem, emotional stability, and self-efficacy, enhancing individual proficiency in physical activities and strengthening resilience in managing daily difficulties [7]. Furthermore, sport and physical activity create the opportunity for social interactions, collaboration, and positive relationships [8]. Despite widespread recognition of its role in promoting physical health and equipping individuals with cognitive and emotional tools to manage stress, physical activity (PA) is also essential for preventing domestic isolation, mitigating technology overuse, and promoting healthier development in the younger population [9].

Addressing the connection between PA and post-COVID mental health is crucial for developing personalized preventive and therapeutic strategies tailored to age and previous difficulties.

The study aims to evaluate the persistence of psychological distress such as anxiety, depression, and post-traumatic stress disorders, across different age groups and to determine whether extracurricular cultural and physical and sport activities can provide resilience strategies in the young population. Unlike previous studies, this research employs an innovative decision-making approach using decision trees to identify the most efficient key predictors of these psychological outcomes.

2. Materials and Methods

2.1. Study Design

A cognitive survey was administered after 4 years of the COVID-19 pandemic (January 2024–June 2024) to evaluate the long-term psychological effects of the pandemic on children and adolescents, focusing on symptoms such as depression, anxiety, and stress. The study also aims to identify whether sports activity contributes to enhancing resilience and mitigating these psychological outcomes.

2.2. Participants

A total of 1702 children and adolescents were recruited through a snowball sampling strategy using an online survey platform (Google Form) or via paper questionnaires administered at school complexes. The inclusion criteria were (a) aged between 8 and 18 years; (b) affiliation with sports clubs; (c) practicing cultural or amateur sports activities; (d) sedentary individuals. The study participants were distributed as follows: by type of activity (athletes, individuals practicing cultural activities, those practicing both sports and cultural activities, sedentary individuals), and by age group (8–12 years and 13–18 years).

Sporting children and adolescents were classified based on individual or team sports. According to the competitive level, athletes were divided into competitive or amateur categories. Athletes were grouped into different categories based on workload (minutes per week).

The study was designed and conducted in accordance with the Declaration of Helsinki and approved by the University Research Committee (CAR-IRB) of the University of Rome "Foro Italico" (CAR 178/2023).

2.3. Procedures

To assess the potential impact on quality of life, levels of depression, anxiety, and perceived stress four years after the COVID-19 pandemic, a cognitive survey was conducted.

The questionnaires were administered in Italy using two methods. The first method involved surveying an online platform (Google Forms). Invitations were sent to National Sports Federations, Sports Promotion Entities, and Cultural Centers. An informative letter was included, explaining the purpose of the research and ensuring confidentiality and anonymity. Personal data were collected anonymously through the use of a personal security code. Informed consent was obtained electronically. Adult participants (aged 18) completed the consent form after reading and accepting the study description. For minors, consent was provided by parents or guardians.

The second survey was conducted in paper format in school settings during curricular hours. Participation was promoted by school principals, who informed families via a circular that provided an overview of the project. After reviewing the document, parents submitted the informed consent forms to the school, which were subsequently delivered to the research team.

In the first section, the survey assesses sociodemographic factors such as age, gender, "type of activity" (sport, cultural activities, both sport and cultural activities, no sport), "training and cultural activities experience" (years), and "physical activity level" (time $\times$ day $\times$ week).

The second section evaluates the quality of life, levels of depression, anxiety, and psychological distress four years after the COVID-19 pandemic, using three different questionnaires: the Impact of Event Scale (IES-8 and IES-15), Generalized Anxiety Disorder Scale (GAD-7), and Center for Epidemiological Studies Depression Scale for Children (CES-DC).

2.4. Screening Questionnaire

2.4.1. Impact of Event Scale

The Impact of Event Scale (IES) questionnaire was used to assess post-traumatic stress disorder (PTSD) in children and adolescents, specifically regarding the psychological impact of the COVID-19 pandemic. This includes factors such as lockdown measures, social isolation, and trauma related to the virus. The goal is to identify the effects of these stressors and evaluate the protective role of physical activity.

Two different databases were used based on the age of the participants: children (aged from 8 to 12 years) underwent the IES-8 [10], while adolescents (aged 13 to 18 years) underwent the IES-15 [11]. Both the IES-8 and IES-15 questionnaires include two subscales to evaluate the symptoms of intrusion (INT) and avoidance (AV). The subscale scores highlight the frequency of specific behaviors. The INT subscale measures the recurrence of trauma-related thoughts, images, dreams, and emotions, while the AV subscale evaluates attempts to suppress those thoughts and feelings. AV also includes elements of emotional numbness and dissociation, which represent an active defensive response.

The IES-8 and IES-15 questionnaires include 8 and 15 items, respectively, and use a Likert scale that ranges from 0 (not at all) to 5 (often).

The IES-8 [10], designed for children aged 8 to 12, shows a strong correlation with the full version (IES-R) and has a cut-off score of 17 or above to identify individuals experiencing stress. The scale showed a strong overall reliability, with a coefficient of 0.84. The INT and AV subscales have achieved reliability values of 0.91 and 0.83, respectively. Furthermore, the IES-8 showed high internal consistency, with a Cronbach's alpha of 0.78 [12]. It has been previously used to assess children's reactions to potentially traumatic events.

The IES-15 [11] is designed for participants aged 13 to 18. A total score of 30 or above indicates a significant stress response syndrome. The subscale scores for INT and

AV help assess the likelihood of these behavioral patterns. The IES-15 shows strong test-retest reliability, with a range of 0.79 to 0.89, and showed satisfactory internal consistency (Cronbach's α = 0.78 to 0.82) [13].

Both versions used in this study have been validated in Italy [14,15].

2.4.2. Generalized Anxiety Disorder Scale

The Generalized Anxiety Disorder Scale (GAD-7) [16], was used to assess the presence and severity of generalized anxiety disorder symptoms in the past two weeks. The GAD-7 includes 7 items, each one with a Likert rating scale from 0 to 3 on a 4-point Likert scale (0 = Not at all; 1 = several days; 2 = more than half the days; 3 = nearly every day). The total score ranges from 0 to 21, with higher scores indicating greater anxiety severity: 0–4 = minimal anxiety; 5–9 = mild anxiety; 10–14 = moderate anxiety; 15–21 = severe anxiety. A score of 10 or higher is generally considered the cutoff for identifying clinically significant anxiety, which requires further evaluation or intervention by a healthcare professional [17]. Furthermore, the GAD-7 demonstrated high reliability, with a Cronbach's alpha of 0.895 [18].

2.4.3. Center for Epidemiological Studies Depression Scale for Children

The Center for Epidemiological Studies Depression Scale for Children (CES-DC) was used to evaluate depressive symptoms in children and adolescents. The CES-DC consists of 20 items that assess the presence and severity of depressive symptoms experienced during the past week. Each item was rated on a 4-point Likert scale, ranging from 0 ("not at all") to 3 ("a lot"). The total score ranges from 0 to 60, with a cut-off score of 15 or higher generally indicating the possible presence of clinically significant depression. The CES-DC has strong internal consistency, as reflected by Cronbach's alpha values of 0.85 [19].

2.5. Statistical Analysis

Descriptive statistics were calculated using percentages (%) for categorical data, while mean, SD, median and inter-quartile ranges were calculated for continuous data.

Furthermore, separated two-step cluster analyses were applied for the two continuous variables (i.e., age and normalized training experience) when considering the samples of GAD and CES-DC, while the same cluster analysis approach was used for normalized training experience only when considering IES-15 and IES-8. The two step cluster analysis was calculated using a Schwarz's Bayesian Criterion (BIC) and including a pre-determined number of clusters (i.e., 3). For the cluster formation, the analysis of the Silhouette measure of cohesion and separation was also performed with values interpreted as 0.0–0.2, poor; 0.2–0.8, fair; and 0.8–1, high [20]; with all cluster analyses revealing fair to high values.

The Shapiro–Wilk test was applied to assess the normal distribution of the dependent variables (i.e., the total scores of GAD, CES-DC, IES-15, and IES-8, the subscales of intrusion and avoidance for IES-15 and IES-8), showing data were non-normally distributed. Therefore, to assess the differences or the variables cultural activity and sex, a Mann–Whitney U test was applied for each dependent variable, while Kruskal–Wallis tests were used to assess the differences for physical activity levels, cluster age, cluster normalized training experience, and type of activity. In case of statistical significance difference, a post hoc analysis using the Mann–Whitney U test with Bonferroni correction was applied.

Successively, separate exhaustive CHAID decision trees using a maximum of three levels about the tree depth, parent node = 100, child node = 50, and including the Pearson's chi-square statistics to split the nodes were used as the machine learning approach. Specifically, total SRTS values for GAD (minimal/mild anxiety vs. moderate/severe anxiety), cut-off values from CES-DC (depressed vs. non-depressed), and IES-8 and IES-15 were

used as dependent variables and sex (male vs. female), age (i.e., 3 clusters), physical activity level (≤120 min, 121–270 min, 271–480 min, >480 min), type of activity (sport, cultural activity, both or none), normalized training experience (i.e., 3 clusters), and cultural activity (yes vs. no) were included in the model as independent variables. Cross-validation was used to assess the robustness of the created tree using 10 as the number of sample folds. The predictive ability of each decision tree model was assessed using the resubstitution method.

All analyses were run using SPSS (IBM, v.29.0, Chicago, IL, USA) and the significance level for the non-parametric tests and the splitting nodes was set at <0.05.

3. Results

The sports participants who completed the questionnaire practiced 45.80% individual sports and 54.20% team sports. The main sports activities practiced were soccer, fencing, rhythmic gymnastics, basketball, dance, swimming, and tennis.

3.1. Cluster Analyses

3.1.1. GAD and CES-DC

According to the analysis for GAD and CES-DC, the three clusters for age had the following mean ± SD: 10.7 ± 1.1 years, 14.1 ± 0.7 years, and 17.4 ± 1.1 years. The normalized training experience showed the following mean ± SD for the three clusters, respectively: 0.05 ± 0.04 AU (low normalized training experience), 0.26 ± 0.07 AU (moderate normalized training experience), 0.54 ± 0.11 AU (high normalized training experience).

3.1.2. IES-15 and IES-8

Regarding the analysis of the IES-15, the three clusters for normalized training experience had the following mean ± SD: 0.04 ± 0.04 AU, 0.23 ± 0.05 AU, 0.46 ± 0.10 AU. Moreover, the normalized training experience showed the following mean ± SD for the three clusters when considering IES-8: 0.11 ± 0.08 AU, 0.66 ± 0.73 AU, 0.39 ± 0.07 AU.

3.2. Traditional Non-Parametric Approach

3.2.1. GAD

No differences in sex, cultural activity, PA level, and type of activity were found for the GAD total score, while a significant difference was found for cluster age and normalized training experience ($p < 0.001$). Post hoc analyses of cluster age revealed that younger participants (i.e., 10.7 ± 1.1 years) had lower GAD scores compared to older participants grouped in cluster 2 ($p < 0.001$) and cluster 3 ($p < 0.001$). Regarding the normalized training experience, higher values of GAD total score were found in participants reporting a lower normalized training experience ($p < 0.001$) and medium normalized training experience ($p < 0.001$) compared to high normalized training experience. The results are shown in Table 1.

Table 1. Results with traditional non-parametric approach of Generalized Anxiety Disorder Scale (GAD) and Center for Epidemiological Studies Depression Scale for Children (CES-DC).

Variable		Total Score GAD		Total Score CES-DC	
		Mean (SD)	Median (IQR)	Mean (SD)	Median (IQR)
Sex	Male	7.6 (4.8)	7.0 (7.0)	21.0 (9.3)	20.0 (14.0)
	Female	7.9 (5.1)	7.0 (7.0)	22.1 (10.1)	21.0 (15.0)
Type of activity	Sport	7.7 (5.0)	7.0 (7.0)	21.4 (9.6)	20.0 (14.0)
	Cultural activity	7.5 (5.4)	6.0 (6.7)	21.4 (11.3)	19.5 (20.0)
	Both sport and cultural activity	7.7 (4.8)	7.0 (7.0)	21.0 (9.2)	20.0 (12.0)
	No activity	8.2 (5.2)	8.0 (8.0)	23.6 (10.6)	23.0 (17.0)

Table 1. *Cont.*

Variable		Total Score GAD		Total Score CES-DC	
		Mean (SD)	Median (IQR)	Mean (SD)	Median (IQR)
Physical activity level	≤120 min/week	7.8 (5.1)	7.0 (7.0)	21.8 (10.6)	20.0 (16.0)
	121–270 min/week	7.4 (4.7)	7.0 (6.0)	21.4 (9.3)	20.0 (13.0)
	271–480 min/week	8.0 (4.9)	7.0 (7.0)	21.5 (9.4)	21.0 (13.0)
	>480 min/week	8.0 (5.1)	7.0 (7.0)	21.6 (9.5)	21.0 (14.0)
Cultural activity	Yes	7.4 (5.0)	7.0 (7.0)	20.5 (9.8)	19.0 (13.0)
	No	7.9 (4.7)	7.0 (7.0)	21.7 (9.0)	21.0 (14.0)
Normalized training experience	Low	8.1 (5.1)	7.0 (7.0)	23.0 (10.1)	22.0 (15.0)
	Medium	8.2 (5.1)	7.0 (8.0)	21.6 (9.6)	21.0 (14.0)
	High	6.8 (4.6)	6.0 (7.0)	19.5 (9.2)	19.0 (14.0)
Age	10.7 (1.1) y	6.6 (4.4)	6.0 (7.0)	19.7 (9.1)	19.0 (14.0)
	14.1 (0.7) y	8.6 (5.2)	8.0 (8.0)	22.7 (10.1)	21.0 (15.0)
	17.4 (1.1) y	8.4 (5.1)	8.0 (7.0)	22.8 (9.8)	22.0 (14.0)

Legend: SD: Stantard Deviation; IQR: Interquartile Range; GAD: Generalized Anxiety Disorder Scale; CES: Center for Epidemiological Studies Depression Scale for Children.

3.2.2. CES-DC

No differences in total score for sex, cultural activity, and PA levels ($p > 0.05$) were found. Differently, differences were evident in cluster age and normalized training experience ($p < 0.001$) and type of activity ($p = 0.036$). Post hoc analyses of age revealed that younger participants (i.e., 10.7 ± 1.1 years) had lower CES-DC values compared to older participants grouped in Cluster 2 ($p < 0.001$) and Cluster 3 ($p < 0.001$), while no differences were evident between Cluster 2 and Cluster 3 ($p > 0.05$). Considering normalized training experience, post hoc analyses showed that participants with a high normalized training experience had lower CES total score compared to participants with low ($p < 0.001$) and medium ($p < 0.001$) normalized training experience. The only post hoc difference found in type of activity included lower CES total score values for sport compared to no activity ($p < 0.05$). The results are shown in Table 1.

3.2.3. IES-15

No effects were evident for cultural activity, normalized training experience, PA levels, and type of activity for any considered dependent variable ($p > 0.05$). Similarly, no differences were evident for sexes when considering total score and intrusion mean ($p > 0.05$), while a difference was evident for avoidance mean ($p = 0.027$). The results are reported in Table 2.

Table 2. Results with traditional non-parametric approach of Impact of Event Scale-15 (IES-15).

Variable		Total Score		Mean Intrusion		Mean Avoidance	
		Mean (SD)	Median (IQR)	Mean (SD)	Median (IQR)	Mean (SD)	Median (IQR)
Sex	Male	16.7 (11.0)	15.0 (16.0)	1.0 (0.9)	0.9 (0.9)	1.6 (1.1)	1.6 (1.6)
	Female	18.1 (12.0)	16.9 (17.0)	1.1 (0.9)	0.9 (1.0)	1.8 (1.2)	1.6 (1.4)
Type of activity	Sport	17.5 (11.7)	16.0 (18.0)	1.1 (0.9)	0.9 (1.4)	1.7 (1.2)	1.6 (1.6)
	Cultural activity	N/A	N/A	N/A	N/A	N/A	N/A
	Both sport and cultural Activity	16.8 (11.5)	15.0 (15.8)	1.1 (0.9)	0.9 (1.3)	1.6 (1.2)	1.4 (1.6)
	No activity	17.3 (10.5)	17.0 (16.0)	1.1 (0.9)	1.0 (1.2)	1.6 (1.0)	1.6 (1.2)
Physical activity level	≤120 min/week	16.4 (11.3)	16.0 (15.0)	1.0 (0.9)	0.9 (1.1)	1.6 (1.1)	1.6 (1.4)
	121–270 min/week	18.6 (11.7)	18.0 (16.0)	1.1 (0.9)	1.0 (1.3)	1.8 (1.2)	1.6 (1.6)
	271–480 min/week	17.9 (11.3)	15.0 (16.3)	1.0 (0.9)	0.9 (1.2)	1.7 (1.1)	1.6 (1.6)
	>480 min/week	16.9 (11.7)	15.0 (19.0)	1.1 (0.9)	0.9 (1.4)	1.6 (1.2)	1.4 (1.6)

Table 2. *Cont.*

Variable		Total Score		Mean Intrusion		Mean Avoidance	
		Mean (SD)	Median (IQR)	Mean (SD)	Median (IQR)	Mean (SD)	Median (IQR)
Cultural activity	Yes	15.7 (10.2)	14.5 (13.5)	1.0 (0.8)	0.9 (0.9)	1.5 (1.1)	1.3 (1.6)
	No	17.5 (11.6)	16.0 (17.0)	1.1 (0.9)	0.9 (1.4)	1.7 (1.2)	1.6 (1.6)
Normalized training experience	Low	17.7 (11.3)	17.5 (17.0)	1.1 (0.9)	1.0 (1.2)	1.7 (1.1)	1.6 (1.4)
	Medium	17.9 (11.8)	16.0 (17.0)	1.1 (0.9)	0.9 (1.3)	1.7 (1.2)	1.6 (1.6)
	High	16.1 (11.4)	14.0 (16.0)	1.0 (0.9)	0.7 (1.3)	1.5 (1.2)	1.3 (1.8)

Legend: SD: Standard Deviation; IQR: Interquartile Range; N/A: Not Available.

3.2.4. IES-8

Higher values for the female participants compared to the male participants were evident for IES-8 total score ($p = 0.014$, ES: $Z = -2.466$) and mean intrusion ($p = 0.040$; ES: $Z = -2.059$). No effect was evident for type of activity, physical activity level, and cultural activity ($p > 0.05$). Moreover, an effect was found for normalized training experience in total score ($p = 0.039$) and mean intrusion ($p = 0.011$). Post hoc analyses showed that low normalized training experience had a lower total score ($p < 0.05$ $Z = -2.542$) and mean intrusion ($p < 0.05$ $Z = -2.935$) compared to medium normalized training experience. The results are shown in Table 3.

Table 3. Results with traditional non-parametric approach of Impact of Event Scale-8 (IES-8).

Variable		Total Score		Mean Intrusion		Mean Avoidance	
		Mean (SD)	Median (IQR)	Mean (SD)	Median (IQR)	Mean (SD)	Median (IQR)
Sex	Male	12.3 (7.6)	12.0 (10.5)	1.4 (1.0)	1.3 (1.5)	1.7 (1.4)	1.5 (2.3)
	Female	13.7 (7.6)	13.5 (11.0)	1.6 (1.0)	1.5 (1.5)	1.9 (1.4)	1.5 (2.3)
Type of activity	Sport	12.9 (7.4)	12.0 (11.0)	1.4 (1.0)	1.3 (1.5)	1.8 (1.4)	1.5 (2.4)
	Cultural Activity	14.3 (8.6)	12.0 (9.8)	2.0 (1.1)	2.3 (1.6)	1.6 (1.5)	1.5 (2.4)
	Both Sport and Cultural Activity	13.3 (8.7)	13.0 (13.3)	1.6 (1.1)	1.5 (2.0)	1.8 (1.5)	1.5 (2.8)
	No Activity	13.0 (6.7)	13.0 (9.0)	1.4 (1.0)	1.5 (1.4)	1.8 (1.3)	1.6 (1.8)
Physical activity level	≤120 min/week	13.2 (7.8)	13.0 (11.3)	1.4 (1.0)	1.3 (1.8)	1.9 (1.4)	1.8 (2.1)
	121–270 min/week	12.0 (7.4)	11.0 (12.0)	1.4 (1.0)	1.3 (1.8)	1.6 (1.3)	1.5 (1.8)
	271–480 min/week	14.2 (7.7)	14.5 (12.0)	1.6 (1.0)	1.5 (1.4)	1.9 (1.4)	1.5 (2.5)
	>480 min/week	12.7 (7.4)	12.0 (11.0)	1.4 (1.0)	1.5 (1.4)	1.8 (1.4)	1.5 (2.8)
Cultural activity	Yes	13.4 (8.7)	12.0 (13.0)	1.6 (1.1)	1.5 (1.9)	1.7 (1.5)	1.5 (2.6)
	No	12.9 (7.4)	13.0 (11.0)	1.4 (1.0)	1.3 (1.5)	1.8 (1.4)	1.5 (2.1)
Normalized training experience	Low	13.7 (7.4)	13.0 (10.5)	1.6 (1.0)	1.5 (1.5)	1.9 (1.3)	1.8 (2.0)
	Medium	12.0 (7.6)	11.0 (12.0)	1.3 (1.0)	1.3 (1.5)	1.7 (1.4)	1.5 (2.5)
	High	13.2 (8.2)	12.0 (12.0)	1.5 (1.0)	1.3 (1.3)	1.9 (1.5)	1.5 (2.8)

Legend: SD: Standard Deviation; IQR: Interquartile Range.

3.3. Decision Trees Results

3.3.1. GAD

The analysis of anxiety revealed that most of the participants showed a minimal/mild anxiety (65.5%), while moderate/severe anxiety represented 34.5% of the sample considered. The decision tree analysis showed age as the only predictor of anxiety with participants aged >12.5 y documenting a moderate/severe anxiety of 39% (Figure 1). The decision tree model reported an error rate of 34%.

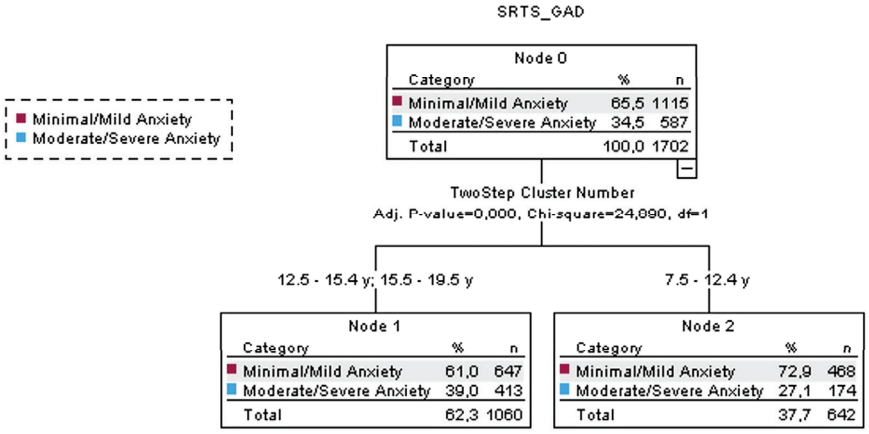


Figure 1. Results with decision tree model of Generalized Anxiety Disorder Scale (GAD): age has been identified as the main predictor of anxiety levels (Generalized Anxiety Disorder Scale).

3.3.2. CES-DC

Considering depressions (CES-DC), 71.3% of the participants showed depressive symptoms (Figure 2). The main predictor is age followed by normalized training experience and PA level. In particular, the highest likelihood of depressive symptoms is present in participants with ≥12.5 y and with moderate-to-low normalized training experience (77.2%). The only case in which participants showed non depression symptoms (59.5%) is shown following the right path of the decision tree, including kids (<12.4 y) with low PA levels (≤120 min/week) but with Moderate-to-High normalized training experience. This decision tree model reported an error rate of 28%.

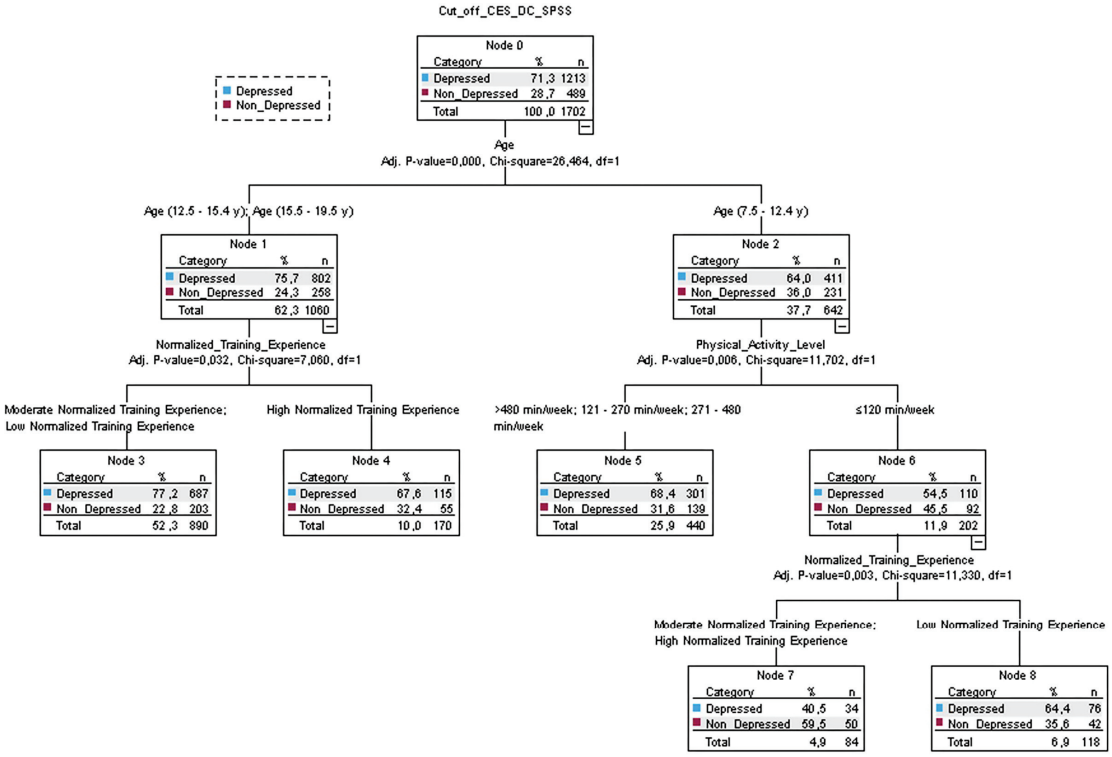


Figure 2. Results with decision tree model on the questionnaire "Center for Epidemiological Studies Depression Scale for Children (CES-DC)": age was the primary predictor for depression. Participants were divided into Node 1 and Node 2: for Node 1, the second predictor for age categories 12.5–15.4 y and 15.5–19.5 y was the training experience, while for Node 2, the main predictor was physical activity level.

3.3.3. IES 15

For this questionnaire, no variable was retained in the model and it was not possible to build the decision tree which remained only with the root node (moderate/severe 24.6% [n = 257] and normal/mild 75.4% [n = 786]).

3.3.4. IES-8

Considering IES-8, 32.9% of the participants showed PTSD symptoms (Figure 3). The main independent variable retained in the model is sex with male participants showing lower percentage of participants with PTSD (28%) compared to female participants (38.1%). Considering males only, PA level was the other variable retained in the model with limited (≤120 min, 121–270 min) or very high (>480 min) PA levels showing the highest values of no PTDS symptoms. Differently, participants reporting 271–480 min of PA per week showed lower percentages (55.8%) of no PTSD symptoms. This decision tree model reported an error rate of 33%.

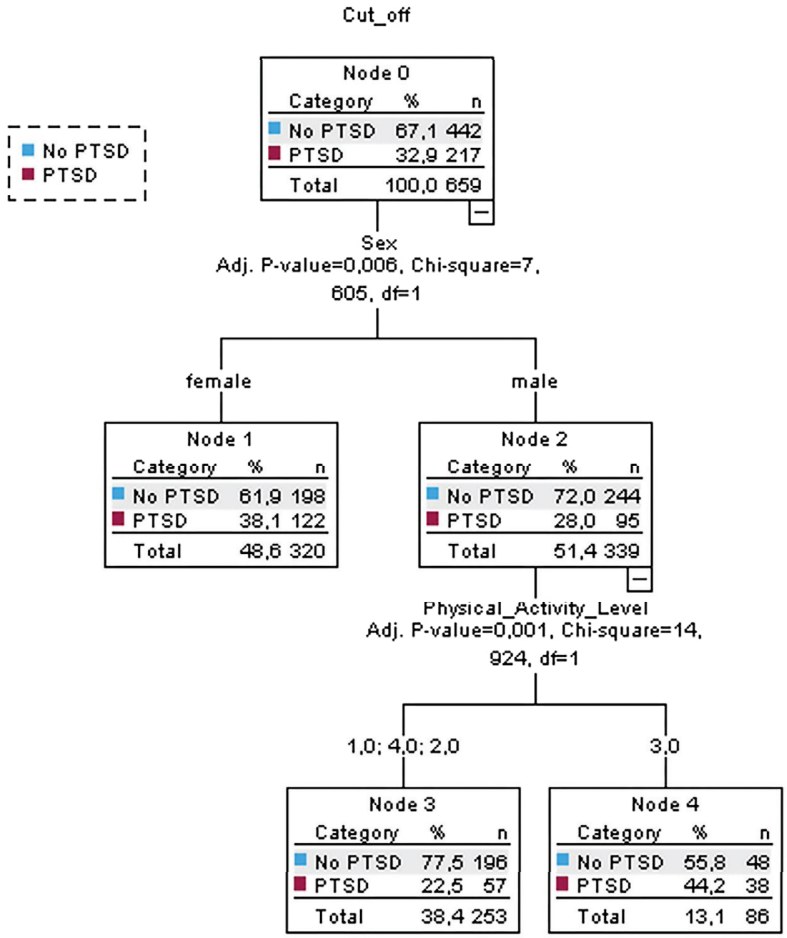


Figure 3. Results with decision tree model of Impact of Event Scale-8 (IES-8): sex was the primary prediction of post-traumatic stress disorder. Participants were divided into Node 1 and Node 2: for Node 2, physical activity level was the main predictor.

4. Discussion

This study aimed to investigate trends in psychological issues among children and adolescents and to evaluate whether extracurricular cultural and sports activities played a protective role in mitigating the long-term effects of the COVID-19 pandemic. The findings confirmed that anxiety, depression, and post-traumatic stress disorder (PTSD) remain

significant concerns, particularly among adolescents, as a significant consequence, among others, of prolonged isolation [21,22].

Participation in cultural activities proved neutral in addressing psychological issues. In contrast, physical activity demonstrated potential in mitigating these adverse effects by enhancing self-esteem and promoting social support, probably due to sport participation, with differences for age, gender, and the level of sports involvement. It was expected that sport participation leads to psychological resilience, providing young people with cognitive as well as emotional tools to counteract stressors [23].

A central aspect of this study concerns the use of an innovative approach using a decision tree that, assessing differences in the key variables, detected a risk profile for participants.

Adolescents are the most impacted age group, exhibiting higher levels of anxiety and depressive symptoms compared to children, with no significant difference observed between Cluster 2 (14.1 $\pm$ 0.7 age years) and Cluster 3 (17.4 $\pm$ 1.1 age years) [24]. The physical and sports activity intervention should therefore particularly involve adolescents, proposing high-impact activities in terms of intensity and duration, to reduce anxiety levels in this group. Decision tree models further highlighted age as the primary predictive factor for anxiety (ranged from moderate to high), while for depression, key predictors included age, normalized sports training experience, and physical activity level, particularly among adolescents. These adolescents were children during the pandemic, and the loss of daily routines likely contributed to heightened anxiety [25]. This is consistent with the understanding that uncertainty—amplified by the disruption of school, social, and sports activities—acts as a key contributor to anxiety [26].

Regarding depression, it should be taken into consideration that adolescents have been more significantly impacted by reduced peer interactions and increased demands for personal responsibility, such as self-directed learning [27]. High-intensity training also proves effective in counteracting depressive symptoms, taking into consideration that adolescents are more affected than children (age as the main predictor). Furthermore, the results highlighted that engaging in sports activities with others could be a solution to counter depression, even though no significant differences were found between team sports and individual sports in the obtained results. Research on psychological development during childhood and adolescence indicates that adolescents are particularly susceptible to social stressors like isolation, loneliness, and boredom and, that symptoms of affective disorders increase markedly during this period [28].

The social dimension of sports and PA helps build meaningful connections, providing an emotional support network for adolescents, enhancing adaptive coping strategies, and supporting emotional well-being. The analysis demonstrated that a greater sports experience, in terms of both duration and intensity, is associated with lower levels of depression and could be a key factor in protecting individuals from psychological issues. Children were less impacted by the pandemic's mental health effects, benefiting from stable home environments and supportive parenting, though high parental stress could still lead to maladaptive responses [29]. However, for children under the age of 12 years, the weekly training load should not be excessively high, suggesting the need for a balanced approach to training [25].

Considering PTSD symptoms, higher levels of PA, ranging from high to very high, were associated with reduced PTSD symptoms in children, while no significant effects were observed in adolescents. Despite gender not being identified as a key factor influencing anxiety and depression, the only significant sex difference was identified in PTSD symptoms in children, with a higher percentage of stress disorders reported in females compared to

males. The imbalance can be attributed both to biological and sociocultural differences between males and females since this difference appears in children [30]. Nevertheless, the results that gender differences in managing stress were found only in children could be explained as follows: adolescents may have a background in physical activity and sports that could have provided them with greater protection, with no gender differences, compared to children [31].

Sports train young people to face continuous challenges, thereby enhancing their resilience skills [32].

The study, however, highlights some limitations: although only a few questionnaires were collected through the snowball sampling method, as the majority were gathered in person during school lessons, we highlight that no stratified random sampling was performed for this small group. Socioeconomic status and prior mental health conditions were not investigated, and this may have introduced bias in the interpretation of the results.

5. Conclusions

This approach underscores the added value of advanced analytical techniques for informing more targeted intervention strategies.

The results of this study highlighted the significant presence of psychological issues among children and adolescents. It is also confirmed in this study that physical activity and sports have proven to be effective strategies in mitigating the long-term psychological impacts of the COVID-19 pandemic.

Promoting regular and balanced physical activity, tailored to age and developmental stages, could be an effective preventive strategy against anxiety, depression, and PTSD symptoms, fostering coping strategies.

Adolescents, who have shown higher vulnerability to psychological distress, particularly require targeted interventions such as activities that emphasize team-based participation and peer interaction. Family involvement also could play a crucial role, especially for younger children. The results of the present study could encourage public health policies and educational programs by emphasizing the importance of physical and school-based activities. Specifically, organizing sports programs within school curricula during school hours could help improve students' post-COVID stress levels.

Author Contributions: Conceptualization, G.D.M., C.d.V. and A.d.C.; methodology, G.D.M., C.d.V. and A.d.C.; validation, A.d.C., G.C. and G.F.; formal analysis, D.C. and G.D.M.; investigation, G.D.M. and C.d.V.; data curation, C.d.V.; writing—original draft preparation, G.D.M., D.C. and A.d.C.; writing—review and editing, G.D.M. and A.d.C.; visualization, G.F.; supervision, A.d.C. and G.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by approved by the University Research Committee (CAR-IRB) of the University of Rome "Foro Italico" (CAR 178/2023, approval date: 16 January 2024).

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

Data Availability Statement: The data are available by request to the corresponding author.

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

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Knowledge of Targeted Muscles and Proper Form in Strength Training: A Cross-Sectional Survey of 1000 Adults Across Age, Sex, and Instructional Experience

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Abstract: With the growing availability of strength training information through online platforms and social media, there is an increasing need to ensure that individuals possess sufficient knowledge to train safely and effectively. Nonetheless, previous studies on strength training literacy have primarily focused on university students and have not adequately examined differences in knowledge across age groups or the roles of training experience and instruction. This study aimed to assess the knowledge of (a) targeted muscle groups and (b) proper form and movement among adults aged 20–69 years and to explore how this knowledge varies by age, sex, and experience in training and professional instruction. A total of 1000 adults (100 males and 100 females in each decade from their 20s to 60s) participated in an online survey. The participants were categorized into three groups according to their training and instructional experience. Knowledge was assessed using 10 items pertaining to targeted muscles and 18 items related to exercise form and movement. Three-way analysis of variance was conducted to analyze the associations between age, sex, and experience. Overall, 75.5% of the participants reported strength training experience, whereas 29.3% had received instruction. Knowledge of the targeted muscle groups was significantly higher in participants in their 60s than in those in their 20s ($p = 0.014$); however, the overall accuracy remained below 60%. No significant effect of instruction on anatomical knowledge was observed. In contrast, both training and instructional experience were positively associated with knowledge of form and movement, although the accuracy remained modest among all groups (50–60%). Sex differences in instructional experience varied by age, with older females reporting higher rates than their male counterparts. In conclusion, knowledge of strength training among adults remains insufficient, particularly regarding anatomical targets. Although instruction enhances the understanding of form and movement, it does not guarantee anatomical literacy. To improve training outcomes and safety, instructional strategies should integrate clear, structured, and pedagogically informed approaches that emphasize movement execution and muscle engagement.

Keywords: training literacy; exercise form and movement; targeted muscle knowledge

1. Introduction

Over the past decades, the means of acquiring strength training knowledge have shifted from printed resources such as books and magazines, and later from television programs and DVDs to digital platforms. This transition has made training information more accessible than ever. In recent years, the availability of such information has further expanded beyond these traditional media to include video platforms, social media, and various websites (e.g., YouTube, Facebook). Importantly, these digital platforms have also enabled individuals—not only experts or publishers—to share training knowledge, marking a notable step in their evolution. While this has promoted broader engagement in strength training, it has also raised concerns regarding variability in information quality and reliability [1,2]. Individuals lacking adequate knowledge may accept inaccurate information uncritically and perform exercises based on it. Consequently, they may fail to gain their intended benefits and face an increased risk of injury due to improper form or technique.

To perform strength training safely and effectively, simply receiving information is insufficient. Individuals must also possess the ability to interpret and apply it accurately. In this regard, understanding fundamental principles of resistance training is indispensable. These include the principle of progressive overload and the manipulation of key training variables—volume, intensity, and frequency—to achieve specific goals related to strength, hypertrophy, or muscular endurance [3–7]. Additional principles such as specificity, consistency, and periodization are essential for long-term progress and injury risk reduction [3–7]. Moreover, muscle growth and strength gains depend not only on resistance exercise but also on adequate sleep, nutrition, and rest [3–7].

Differentiating compound lifts (e.g., squat, bench press, deadlift) from single-joint exercises is also important for safe and effective training initiation. Before applying these broader principles, individuals should understand which muscles each exercise targets and how to perform movements with proper form. Hence, assessing the current state of such knowledge and exploring its association with factors such as training experience and instruction are both essential. These insights are crucial in shaping future educational strategies and training practices.

Previous studies [8–13] on knowledge related to strength training have primarily focused on university students. For instance, Oshita et al. [9,10] asked participants to identify the primary muscles used in specific exercises such as squats and found that many identified the quadriceps muscles. Notably, even among those with regular exercise habits, approximately half failed to recognize the gluteal muscles as a primary target, and some selected unrelated areas such as the neck or shoulders. Similarly, Kobayashi et al. [8] reported that nearly 40% of students with strength training experience mistakenly identified lat pulldown, a back exercise, as targeting the chest. These findings consistently indicate limited strength training literacy among young adults, particularly university students, even among those with prior training experience, and suggest that professional instruction may play a critical role in fostering accurate anatomical understanding.

Although these studies were limited to both age range and focus, it remains unclear whether similar patterns hold across other age groups. They primarily examined anatomical knowledge, whereas critical components such as proper form and movement, which are closely linked to safety and effectiveness, were largely overlooked. For instance, older individuals may benefit from greater life experiences or lack sufficient exposure to strength training. Examining how knowledge and instruction interact across a broader age range is crucial for developing effective educational strategies that respond to diverse populations.

Against this background, the present study targeted a broad age range of adults, from their 20s to 60s, with the following two main objectives: (1) to examine knowledge of the targeted

muscle groups in strength training and (2) to assess the knowledge pertaining to proper form and movement, which are critical for the safe and effective execution of strength exercises. To facilitate these assessments, representative muscle areas such as the chest, quadriceps, back, and hamstrings were selected, and the participants' knowledge was measured using typical exercises associated with each area. The knowledge of form and movement was evaluated using representative exercises based on visual materials. Additionally, to allow for a more precise analysis of the association between knowledge and experience, participants were categorized into three groups according to their training history and experience of receiving instruction.

We hypothesized that individuals with training experience—particularly those who had received instruction—would demonstrate higher knowledge scores regarding targeted muscle groups, as well as proper form and movement, compared with individuals without such experience. We further expected that age and sex would be associated with differences in knowledge levels.

2. Materials and Methods

2.1. Study Design and Participants

This study employed a cross-sectional design and conducted an online survey platform. Participants were recruited through a commercial survey company (Cross Marketing Inc., Tokyo, Japan) that distributed survey invitations to individuals registered on the online panel. The recruitment targeted adults in their 20s to 60s, stratified by age and sex. Specifically, 100 males and 100 females were recruited from each decade-based age group (20s, 30s, 40s, 50s, and 60s), resulting in a total sample size of 1000 participants (n = 1000).

Recruitment was closed once these quotas were filled. While this quota sampling ensured balanced distributions across age and sex, the use of a commercial panel does not guarantee full representativeness of the general population. Inclusion criteria were age 20–69 years, residence in Japan. Exclusion criteria included incomplete responses or clearly inconsistent response patterns (e.g., choosing the same option for all items without variation). Prior to answering the questionnaire, the participants were presented with an informed consent form on the initial page of the web-based survey. Only those who provided informed consent were permitted to participate. The study protocol was conducted in accordance with the Declaration of Helsinki and approved by the Research Ethics Committee of Kyoto Institute of Technology (approval no: 2023-55, date: 2 October 2023).

2.2. Measures

The survey consisted of questions designed to assess knowledge of (a) targeted muscle groups and (b) proper form and movement during strength training. In addition, participants were asked about their training experience and their experience receiving instructions.

2.2.1. Assessment of Knowledge of Targeted Muscle Groups

Knowledge of the targeted muscle groups was assessed using 10 items derived from four representative exercises: squat, leg extension, lat pulldown, and push-up. For each item, participants responded using a five-point Likert scale: "strongly agree," "somewhat agree," "neither agree nor disagree," "somewhat disagree," and "strongly disagree." Responses of "strongly agree" and "somewhat agree" were categorized as affirmative, while "somewhat disagree" and "strongly disagree" were categorized as negative. Responses of "neither agree nor disagree" were excluded from the calculation, as they did not indicate correct knowledge. When participants selected either an affirmative or negative response, their answers were evaluated as correct or incorrect, respectively, based on the corresponding target muscle group. The total score ranges from 0 to 10, with one point awarded for each correct response.

2.2.2. Assessment of Knowledge of Proper Form and Movement

Knowledge of proper form and movement was assessed using 19 items based on the same four exercises used to assess knowledge of the targeted muscle groups: squat, leg extension, lat pulldown, and push-up. One item was excluded from the analysis because it was not directly related to form or movement, resulting in 18 items included in the final analysis. The evaluation method was identical to that used for the knowledge of the targeted muscle groups, as described in section (a). Items were developed with reference to the official textbook of the National Strength and Conditioning Association (NSCA) [14] and were customized to fit the aims of this study. The item pool was initially developed and reviewed by the first author, who has practical experience in strength training instruction, and was further refined in discussion with co-authors to ensure clarity and appropriateness. This process ensured face validity.

2.2.3. Training Experience and Experience of Receiving Instruction

To assess the participants' strength training experience, the survey included eight items related to past engagement in training and instructional contexts (e.g., the use of free weights, resistance machines, participation in group classes or personal training, attendance at lectures, and receipt of professional instruction). In addition, participants were shown photographs of four representative exercises—squat, leg extension, lat pulldown, and push-up (Figure 1—and asked to select one of five response options: "currently doing," "have done in the past," "have not done but know the exercise," "have seen it but don't know the details," and "completely unfamiliar." Participants who answered "yes" to any of the eight training/instruction items or selected either "currently doing" or "have done in the past" for any of the four exercises were classified as having strength training experience.

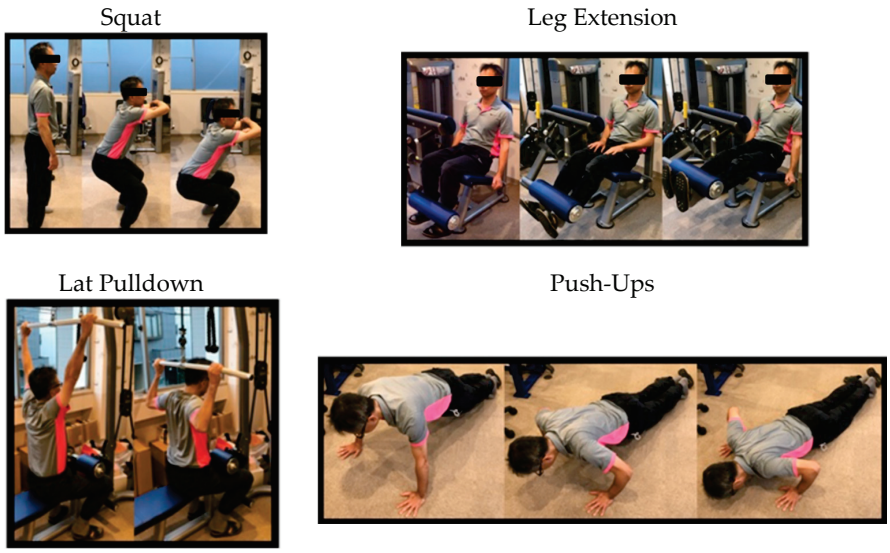


Figure 1. Demonstration of exercises included in the questionnaire.

Five items were included to assess the participants' experience of receiving instructions. The participants were asked whether they had ever received instruction in strength training, received instruction from a professional (e.g., a trainer or fitness instructor), attended a lecture or seminar, received personal training, or participated in studio-based group classes. Each item used a binary response format ("yes" or "no"). Participants who answered "yes" to any of these items were classified as having received instructions. This classification was based on the participants' subjective judgments, regardless of the frequency, content, or format of instruction.

Based on the combination of training experience and experience receiving instruction, participants were categorized into the following three groups: no training experience, training experience without experience receiving instruction, and training experience with experience receiving instruction.

The full list of assessment items is provided in Table S1.

2.3. Statistical Analysis

First, cross-tabulations by age group and sex were conducted to examine differences in the distribution of strength training experience and experience of receiving instruction. The chi-square (χ^2) test of independence was then performed. When significant differences were found, adjusted residuals were examined to identify specific group differences. In addition, effect sizes were calculated using the phi coefficient.

Subsequently, two separate three-way analyses of variance (ANOVAs) were conducted to analyze the participants' knowledge of (a) targeted muscle groups and (b) proper form and movement. In both analyses, the dependent variable was the number of correct responses. The between-subject factors were age group (five levels: 20s, 30s, 40s, 50s, and 60s), sex (male, female), and training experience (three groups: no training experience, training experience without experience of receiving instruction, and training experience with experience of receiving instruction).

When significant interactions were detected, simple main effects were examined to explore specific group differences. For significant main effects, Bonferroni correction was applied to adjust for multiple comparisons. Effect sizes for the ANOVAs were calculated using eta squared (η^2) to assess the magnitude of observed differences.

All statistical analyses were performed using IBM SPSS Statistics version 27 (IBM Corp., Armonk, NY, USA). The significance level was set at $p < 0.05$.

3. Results

3.1. Participant Characteristics and Distributions of Training Experience

Out of 1000 participants, 755 (75.5%) reported having strength training experience (415 males and 340 females). Among those with training experience, 221 (29.3%) reported having experience of receiving instructions. The overall distributions of training and instructional experience are illustrated in Figure 2, and their breakdowns by age group and sex are presented in Figure 3.

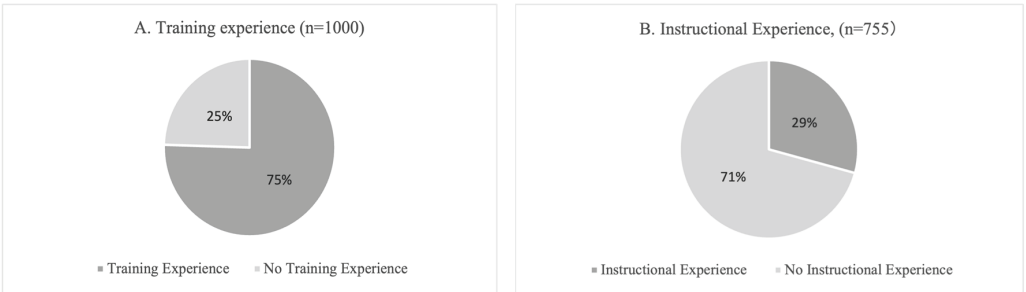


Figure 2. Distribution of training and instructional experience among participants. (**A**) Training experience among all participants (n = 1000; Male n = 500, Female n = 500). (**B**) Instructional experience among participants with training experience (n = 755). Values represent percentages of participants in each category. Training Experience = participants who reported engaging in strength training; Instructional Experience = participants with training experience who had received professional instruction.

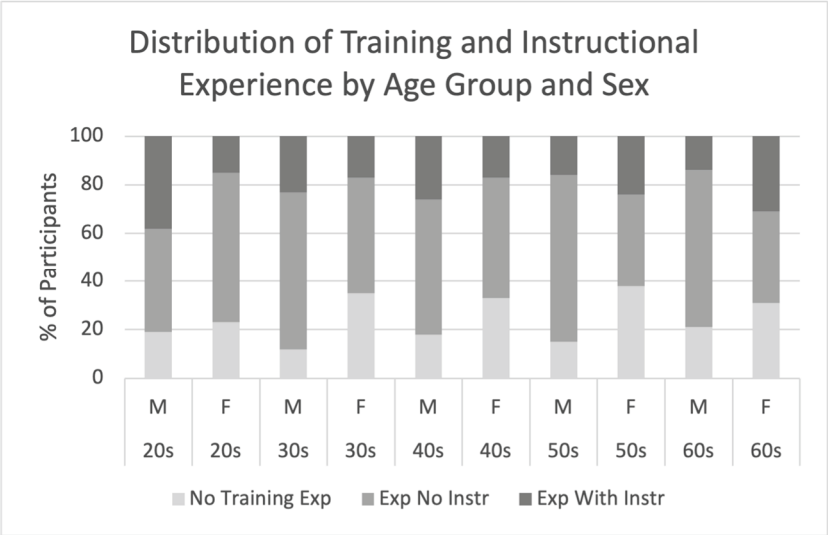


Figure 3. Distribution of training and instructional experience by age group and sex. (n = 1000; Male n = 500, Female n = 500). Bars represent the proportions of participants in each category. No Training Exp = participants without strength training experience; Exp No Instr = participants with training experience but without professional instruction; Exp With Instr = participants with training experience and professional instruction.

Based on the combination of training experience and experience receiving instruction, participants were categorized into three groups: (1) no training experience, (2) training experience without experience receiving instruction, and (3) training experience with experience receiving instruction. The proportions of these groups according to age and sex are shown in Table 1. When the two groups were combined according to training experience (with and without experience in receiving instruction), the overall proportion of participants with training experience was approximately 80% among males and 70% among females across all age groups.

To examine the effects of age and sex on the distribution of training experience and experience of receiving instructions, cross-tabulations were conducted, followed by the chi-square test of independence. The results revealed significant differences by age group for both males and females (χ^2 = 25.77, p = 0.001). The adjusted residuals indicated that, among males, the proportion of those with training experience and experience of receiving instruction was significantly higher in their 20s and significantly lower in their 50s and 60s. Among females, the proportion of those with training experience but without experience of receiving instruction was significantly higher in their 20s, whereas the proportion of those with no training experience was significantly lower. In contrast, in the 60s group, the proportion of females with training experience and experience of receiving instruction was significantly higher than in the other age groups.

A cross-tabulation analysis also revealed a significant sex difference (χ^2 = 20.97, p = 0.007). Adjusted residuals showed that in the 20s group, females were significantly more likely to report training experience without receiving instructions, while males were significantly more likely to report both training experience and receiving instructions. In the 30s–50s group, females were significantly more likely to have no training experience, whereas males were more likely to have training experience without receiving instruction. In the 60s group, females were significantly more likely to report both training experience and experience of receiving instruction.

Table 1. Participant training experience by age group and gender (n = 1000; male n = 500, female n = 500). Values represent the number of participants and percentages within each category.

Male	**No Exp.**		**Exp-No Instr.**		**Exp-Instr.**		**Total**
Age Group	***n***	**Adjusted Residuals**	***n***	**Adjusted Residuals**	***n***	**Adjusted Residuals**	
20s	19	0.6	43	−3.8	38	3.9	100
30s	12	−1.5	65	1.2	23	−0.1	100
40s	18	0.3	56	−0.8	26	0.7	100
50s	15	−0.6	69	2.1	16	−2.0	100
60s	21	1.2	65	1.2	14	−2.5	100
Total	85		298		117		500
Female	No Exp.		Exp-No Instr.		Exp-Instr.		Total
Age Group	*n*	Adjusted residuals	*n*	Adjusted residuals	*n*	Adjusted residuals	
20s	23	−2.2	62	3.3	15	−1.6	100
30s	35	0.7	48	0.2	17	−1.0	100
40s	33	0.2	50	0.6	17	−1.0	100
50s	38	1.4	38	−2.1	24	0.9	100
60s	31	−0.2	38	−2.1	31	2.8	100
Total	160		236		104		500

Adjusted residuals > |1.96| indicate significant deviation from expected counts ($p < 0.05$). Groups were divided into: –No Experience (No Exp.) = participants without strength training experience; –Experience without Instruction (Exp-No Instr.) = participants with training experience but without professional instruction; –Experience with Instruction (Exp-Instr.) = participants with training experience and professional instruction.

Further analysis of sex differences in the experience of receiving instruction by age group showed a notable trend: in the 20s group, 46.9% of males had received instruction compared to only 9.5% of females. Conversely, in the 50s and 60s groups, the proportion of males who had received instruction was the lowest at 18.8% and 17.7%, respectively, whereas the corresponding proportions among females were higher at 38.7% and 44.9%, respectively. This finding suggests a reversal of the sex gap in instructional experience among the older age groups.

3.2. Results: Knowledge of Targeted Muscle Groups

Table 2 presents the means and standard deviations for the number of correct responses to the 10 questions assessing participants' knowledge of the muscle groups targeted by specific strength training exercises, categorized by age group, sex, and experience of training and receiving instruction.

Three-way ANOVA was conducted with age group (five levels: 20s–60s), sex (male, female), and training experience (three groups: no training experience, training experience without experience of receiving instruction, and training experience with experience of receiving instruction) as the between-subject factors.

Table 2. Mean ± standard deviation of correct responses to anatomical knowledge questions (Q3) by age group, sex, and training experience (n = 1000; male n = 500, female n = 500).

Age Group	Male			Female			Total
	No Exp.	Exp-No Instr.	Exp-Instr.	No Exp.	Exp-No Instr.	Exp-Instr.	
20s	3.11 ± 2.96	6.00 ± 2.05	5.84 ± 1.70	4.70 ± 2.80	5.76 ± 1.63	5.27 ± 1.79	5.42 ± 2.20
30s	3.75 ± 2.49	6.15 ± 1.69	6.26 ± 1.60	5.49 ± 2.16	5.33 ± 2.34	6.24 ± 1.64	5.72 ± 2.06
40s	4.28 ± 2.16	5.93 ± 2.01	6.27 ± 1.25	4.48 ± 2.62	6.04 ± 1.94	6.18 ± 1.91	5.64 ± 2.14
50s	3.47 ± 2.56	5.86 ± 2.00	6.50 ± 1.37	4.76 ± 2.39	5.82 ± 2.02	6.33 ± 1.61	5.57 ± 2.17
60s	4.29 ± 2.57	5.97 ± 1.74	7.29 ± 1.33	5.90 ± 2.07	5.34 ± 2.02	6.23 ± 1.86	5.80 ± 2.04
Total	3.80 ± 2.56	5.98 ± 1.88	6.28 ± 1.54	5.08 ± 2.43	5.67 ± 1.98	6.11 ± 1.77	5.63 ± 2.12

Values represent mean ± standard deviation for number of correct answers (range: 0–10). No significant main effect of instruction was observed ($p > 0.05$), although participants with training experience scored significantly higher than those without ($p < 0.001$). Groups were divided into –No Experience (No Exp.) = participants without strength training experience; –Experience without Instruction (Exp-No Instr.) = participants with training experience but without professional instruction; –Experience with Instruction (Exp-Instr.) = participants with training experience and professional instruction.

No significant three-way or two-way interactions involving age were found (age × sex × experience: F(8, 970) = 1.117, p = 0.349, η^2 = 0.009; age × sex: F(4, 970) = 0.251, p = 0.909, η^2 = 0.001; age × training experience: F(8, 970) = 1.775, p = 0.078, η^2 = 0.014). However, there was a significant main effect of age group (F(4, 970) = 2.612, p = 0.034, η^2 = 0.011). Post hoc comparisons using the Bonferroni method revealed that participants in their 60s (M = 5.80, SD = 2.04) scored significantly higher than those in their 20s (M = 5.42, SD = 2.20, p = 0.014).

A significant interaction between sex and training experience was also observed (F(2, 970) = 13.492, $p < 0.001$, η^2 = 0.027). A simple main effects analysis indicated that among participants with no training experience, females (M = 5.08, SD = 2.43) scored significantly higher than males (M = 3.80, SD = 2.56, $p < 0.001$). In contrast, no significant sex differences were found among participants with training experience, regardless of whether they had received instruction (without instruction: p = 0.070; with instruction: p = 0.178).

Furthermore, within each sex, participants with training experience scored significantly higher than those with no training experience (males, $p < 0.001$; females, p = 0.001). However, among participants with training experience, the presence or absence of experience in receiving instructions was not associated with significant differences in scores (males, p = 0.154; females, p = 0.333). These results are summarized in Table 3.

Table 3. Summary of three-way ANOVA results for anatomical knowledge scores (Q3) among participants (n = 1000 adults, stratified by age and sex).

Source of Variation	df	F	p-Value	η^2
Age	4970	2.612	0.034	0.011
Sex	1970	1.794	0.181	0.002
Training Experience	2970	49.748	<0.001	0.093
Age × Sex	4970	0.251	0.909	0.001
Age × Training Experience	8970	1.775	0.078	0.014
Sex × Training Experience	2970	13.492	<0.001	0.027
Age × Sex × Experience	8970	1.117	0.349	0.009

df = degrees of freedom; η^2 = partial eta squared.

3.3. Knowledge of Proper Form and Movement

Table 4 shows the means and standard deviations for the number of correct responses to 18 questions assessing knowledge related to the appropriateness of form and movement during strength training exercises, categorized by age group, sex, and experience of training and receiving instructions.

Table 4. Mean ± SD of correct responses to questions on form and movement (Q4 and Q5) by gender, age group, and training experience (n = 1000; male n = 500, female n = 500).

	Male			**Female**			**Total**
	No Exp.	**Exp-No Instr.**	**Exp-Instr.**	**No Exp.**	**Exp-No Instr.**	**Exp-Instr.**	
20s	4.26 ± 3.77	9.77 ± 4.24	10.95 ± 3.33	6.43 ± 4.71	9.48 ± 3.55	9.67 ± 4.13	8.99 ± 4.30
30s	5.75 ± 4.49	9.94 ± 4.27	11.65 ± 2.90	7.17 ± 3.94	8.60 ± 4.03	9.59 ± 3.78	9.05 ± 4.23
40s	6.39 ± 4.77	9.02 ± 4.82	12.19 ± 3.48	6.48 ± 4.47	9.36 ± 4.20	10.29 ± 3.55	8.97 ± 4.65
50s	5.33 ± 5.67	9.17 ± 4.88	11.63 ± 4.77	5.63 ± 5.10	7.95 ± 3.86	11.75 ± 2.88	8.49 ± 5.02
60s	5.86 ± 4.75	8.65 ± 5.19	11.21 ± 4.53	7.71 ± 5.29	8.29 ± 3.65	9.77 ± 4.96	8.50 ± 4.93
Total	5.51 ± 4.64	9.28 ± 4.72	11.49 ± 3.63	6.66 ± 4.72	8.84 ± 3.87	10.27 ± 4.03	8.80 ± 4.63

Values represent mean ± standard deviation of correct responses (score range: 0–10). No significant main effect of instruction was found ($p > 0.05$), but participants with training experience scored significantly higher than those without ($p < 0.001$). Groups were divided into –No Experience (No Exp.) = participants without strength training experience; –Experience without Instruction (Exp-No Instr.) = participants with training experience but without professional instruction; –Experience with Instruction (Exp-Instr.) = participants with training experience and professional instruction.

Three-way ANOVA was conducted with age group (five levels), sex (male, female), and training experience (three groups: no training experience, training experience without experience of receiving instruction, and training experience with experience of receiving instruction) as the between-subject factors.

No significant interactions involving age were found (age × sex × training experience: $F(8, 970) = 0.599$, $p = 0.779$, $\eta^2 = 0.005$; age × sex: $F(4, 970) = 0.254$, $p = 0.907$, $\eta^2 = 0.001$; age × training experience: $F(8, 970) = 1.261$, $p = 0.260$, $\eta^2 = 0.010$). In addition, the main effect of age group was not significant ($F(4, 970) = 0.358$, $p = 0.838$, $\eta^2 = 0.001$), indicating no substantial age-related differences in form and movement knowledge.

However, a significant interaction was found between sex and training experience ($F(2, 970) = 4.658$, $p = 0.010$, $\eta^2 = 0.010$), prompting a simple main effects analysis. Among the participants with no training experience, females scored significantly higher than males ($p = 0.049$). In contrast, among those with both training experience and experience in receiving instructions, males outperformed females ($p = 0.033$). No significant sex difference was found among participants with training experience but no experience of receiving instruction ($p = 0.137$).

Further comparisons across training experience groups within each sex revealed that for both males and females, participants with training experience but no experience of receiving instruction scored significantly higher than those with no training experience (males, $p < 0.001$; females, $p < 0.001$). Moreover, those with both training experience and experience of receiving instruction scored significantly higher than those with training experience but no instruction (males, $p < 0.001$; females, $p = 0.015$). A summary of the three-way ANOVA results for knowledge of proper form and movement is presented in Table 5.

Table 5. Summary of three-way ANOVA results for Form and Movement scores among participants. (n = 1000 adults, stratified by age and sex).

Source of Variation	df	F	p-Value	η^2
Age	4970	0.358	0.838	0.001
Sex	1970	0.583	0.445	0.001
Training Experience	2970	64.607	0.000	0.118
Age × Sex	4970	0.254	0.907	0.001
Age × Training Experience	8970	1.261	0.260	0.010
Sex × Training Experience	2970	4.658	0.010	0.010
Age × Sex × Experience	8970	0.599	0.779	0.005

df = degrees of freedom; η^2 = partial eta squared.

4. Discussion

4.1. Strength Training and Instructional Experience by Age and Sex

This study revealed that 75.5% of the respondents reported engaging in strength training at some point in their lives. Across all age groups, approximately 80% of males and 70% of females had such experience, suggesting that strength training is relatively widespread regardless of sex or age. However, this classification is based on lifetime experience rather than frequency or continuity, which may partially explain the high percentages. By contrast, a national survey conducted by the Sasakawa Sports Foundation [15] reported that only 12% of Japanese individuals engage in strength training at least once a year, indicating that strength training has not yet been established as a regular part of their daily lives.

Among those with training experience, approximately 30% reported having received instruction, a proportion comparable to that observed in previous research among university students [14]. Notably, this study provides valuable insights into the instructional experiences of adults in their 30s and older, a population that has been less frequently examined in prior work. The findings showed that among individuals in their 50s and 60s, the proportion of those with instructional experience was lower for males but higher for females than for other age groups.

Among participants in their 50s and 60s, a greater proportion of women reported having received instruction compared to men. Notably, this sex difference does not appear to be attributable to disparities in overall strength training experience, as both sexes exhibited comparable levels of training engagement. Data from the present study revealed that men in their twenties had significantly more instructional experience than women in the same age group. This earlier exposure to guidance may have diminished their perceived need for subsequent instruction in later adulthood, thereby contributing to the observed disparity in instructional experience. However, it should be noted that the current data reflect the experiences of today's younger generation, and it remains unclear whether men who are now in their 50s and 60s had similarly greater access to instruction in their twenties. Therefore, caution is warranted when drawing generational comparisons or inferring causal relationships based on these findings.

4.2. Discussion: Knowlwdge of Targeted Muscle Groups

This study found that participants in their 60s scored significantly higher than those in their 20s on knowledge of the muscle groups targeted by specific strength training exercises. However, no significant differences were observed among those in their 20s and 50s. Previous studies focusing on university students have reported insufficient knowledge

and misconceptions regarding the relationship between training exercises and targeted muscle groups [8–13]. The present study extends these findings by encompassing a broader age range from 20s to 60s, thereby offering a more comprehensive view of age-related trends in training-related knowledge.

The relatively higher scores observed among individuals in their 60s may reflect increased health awareness and interest in physical activity for disease prevention, which is commonly observed with aging. In addition, recent improvements in access to training information through online video platforms and social media may have facilitated the acquisition of basic training knowledge among older adults. Despite this, the overall accuracy remained modest; scores among participants in their 20s through 50s hovered at around 50%, and even among those in their 60s, the rate of correct answers did not exceed 60%. These results indicate that knowledge of the targeted muscle groups is generally limited across all age groups.

Inaccurate knowledge of the targeted muscle groups can result in the selection of inappropriate exercises, potentially leading to mismatches between training objectives and execution. This, in turn, may compromise the effectiveness of training and increase the risk of injury owing to the poor form or overload of the unintended muscle groups.

Participants with training experience demonstrated significantly higher accuracy in identifying targeted muscle groups, a finding consistent with those of previous studies [8,9]. This suggests that engaging in training may enhance an individual's awareness of the relationship between exercise and muscle groups. However, even among participants with training experience, the correct answer rates remained at approximately 60%, highlighting that experiential learning alone may not be sufficient for acquiring accurate and consistent knowledge.

By contrast, no significant difference in knowledge accuracy was found based on whether the participants had received professional instruction. This suggests that receiving instruction alone does not necessarily translate into higher anatomical literacy. Supporting this interpretation, prior research has shown that even individuals who received instructions continued to exhibit low accuracy when asked to identify the muscles targeted by basic exercises such as push-ups and squats [8]. The present study reinforces this notion, revealing no appreciable difference in knowledge across instructional experience groups regardless of age. These findings imply that, while instruction may play a role in guiding behavior or motivation, its impact on foundational knowledge acquisition may be limited unless coupled with targeted educational interventions.

4.3. Knowledge of Training Form and Movement

This study found no significant age-related differences in knowledge of proper training forms and movements. While previous studies have examined anatomical knowledge among university students [8,10], few have addressed form- and movement-related literacy across a wide range of age groups. The present study is, therefore, novel in that it provides an overview of the current knowledge levels of individuals in their 20s through 60s, offering valuable insights into the development of future training education and instructional strategies. However, overall accuracy remained below 50% across all age groups, with a mean score of approximately 47%. These findings suggest that literacy regarding training forms and movements is inadequate. A lack of such knowledge may compromise training effectiveness and increase the risk of injury due to improper technique.

By contrast, participants with strength training experience scored significantly higher than those without. Forms and movements are typically acquired through repeated practice accompanied by proprioceptive and visual feedback. This suggests that practical experience

may contribute to improved knowledge. Nevertheless, even among those with training experience, the accuracy remained at around 50%, indicating that experience alone was insufficient for developing adequate literacy. Therefore, training experience should be complemented by more structured and continuous knowledge support to enhance the understanding of correct forms and movements.

Furthermore, participants with experience receiving instructions demonstrated significantly higher levels of knowledge than those without such experience. This implies that instruction plays an important role in promoting accurate understanding. Since form and movement are visually observable during training, instructors can provide real-time feedback, enabling more effective error correction. Oshita et al. [10] emphasized the importance of receiving professional guidance to prevent injuries and ensure correct execution. In contrast, the present study found no significant difference in anatomical knowledge (i.e., knowledge of the targeted muscle groups) between those with and without instructional experience. This may be due to the inherently less observable nature of anatomical targeting; trainers may not detect such misconceptions unless they are explicitly reported by trainees. Consequently, instructions may prioritize an observable form over internal muscle activation.

It is also notable that even among those who received instruction, the average accuracy of form and movement remained at approximately 60%. This indicates that, while instruction supports knowledge acquisition, it does not guarantee sufficient understanding. To improve training literacy effectively, instructional practices should include well-structured explanations, step-by-step demonstrations, and concrete examples that facilitate comprehension. A shift toward more intentional and pedagogically informed approaches may be necessary to bridge this knowledge gap.

4.4. Implications for Strength Training Instructors

This study found that, while knowledge of training form and movement was positively associated with both training and instructional experience, knowledge regarding the specific muscle groups targeted by exercises remained insufficiently developed across all participant groups. One possible explanation is that in practical training settings, instructions tend to prioritize correcting observable movement patterns rather than fostering an anatomical understanding of muscle activation.

In typical instructional scenarios, trainers often begin by explaining which muscles should be engaged in a given exercise, followed by demonstrations of the correct form. However, even when trainees successfully replicate the instructed movements, they may still experience uncertainty regarding which muscles are actually being used. In such cases, trainers may employ supplementary techniques such as visual modeling or tactile cues to highlight the intended muscle activation. Nevertheless, many trainees reported difficulty developing sensory awareness of the targeted muscle areas.

These challenges can result in instructions that become overly routine and mechanistic, with a limited impact on conceptual understanding or perceived training efficacy. To address this issue, it is essential that trainers move beyond purely prescriptive guidance and actively communicate the rationale behind each exercise, that is, what its intended effects are and which specific muscles it targets. Incorporating explanations that integrate verbal descriptions, visual demonstrations, and sensory feedback can promote a more embodied and meaningful understanding among trainees.

Furthermore, although access to training-related content has significantly increased through online platforms such as YouTube and social media, this information is typically delivered in a unidirectional manner and lacks opportunities for interactive clarification or

corrective feedback. Consequently, misconceptions may persist or be reinforced. Direct in-person instruction remains essential to facilitate accurate comprehension and safe practice, particularly for novice trainees or those lacking prior experience.

To foster more robust training literacy, instructional strategies should aim not only to improve mechanical execution but also to develop conceptual understanding. Trainers should adopt a pedagogical orientation characterized by deliberate communication, individualized feedback, and structured progression. Such an approach can enhance both the effectiveness and safety of strength training, particularly in the general population with limited prior exposure.

4.5. Limitations

This study has several limitations that should be acknowledged.

First, although it covered a broad age range from the 20s to the 60s, it did not include older adults or teenagers. Thus, the findings cannot be generalized to populations outside this age range.

Second, the sample consisted exclusively of Japanese adults, which may restrict the generalizability of the results to other cultural contexts. Future research should examine diverse populations to provide a more comprehensive understanding.

4.6. Future Directions

When interpreting the findings of this study, it is important to consider the individual and contextual factors that may underlie variations in training knowledge and experience. While this study examined whether participants had strength training experience or had received instructions, it did not investigate the broader determinants of these experiences, such as personal interests, lifestyle habits, physical and psychological characteristics, social support systems, or varying levels of awareness across sexes and age groups. For example, the relatively high rate of instructional experience observed among older female participants may be influenced by greater health consciousness or the availability of supportive environments such as community fitness programs.

In addition, differences in knowledge and behavioral patterns may be shaped by the specific goals associated with training, whether oriented toward health maintenance, athletic performance, or esthetic objectives, such as body shaping. The current study assessed knowledge primarily through a correct/incorrect judgment format but did not address how such knowledge is applied to actual training behavior. Although knowledge is generally regarded as contributing to safe and effective practices, it does not necessarily translate directly into higher-quality execution or outcomes. Individuals may develop appropriate techniques through imitation, embodied feedback, or routine practices, even in the absence of explicit knowledge. Thus, it is essential to critically examine the often-assumed causal link between knowledge acquisition and behavioral quality.

Future research should adopt a more integrated approach to explore how cognitive, psychological, and social factors affect training-related knowledge. It is also important to assess how such knowledge influences not only behavioral choices but also training outcomes over time. Educational interventions and strategies for behavioral change should be designed and evaluated in this broader context. Longitudinal studies, in particular, could offer insights into how training literacy develops, is retained, and influences ongoing behavior. Moreover, the present study classified instructional experience as present or absent without evaluating the instructional quality, frequency, or expertise of the instructor. These aspects likely substantially influence the depth and accuracy of knowledge retention. Future studies should, therefore, explore the qualitative features of instruction to identify

more effective educational practices and optimize training support strategies. In addition, while this study assessed knowledge of targeted muscles and proper form, it did not directly measure muscular activity during exercise. Incorporating such data could provide further insight into the relationship between knowledge and actual muscle engagement.

5. Conclusions

This cross-sectional study aimed to clarify the current state of training-related knowledge among adults aged 20–69 years. A key contribution lies in its inclusion of both anatomical knowledge—specifically, understanding which muscles are targeted by particular exercises—and knowledge of the correct form and movement, the latter of which has received less attention in prior research. The participants were classified based on their strength training and instructional experience, allowing for a multifaceted analysis of how such experience relates to their knowledge levels.

The results revealed that individuals with strength training experience demonstrated significantly higher knowledge in both domains, suggesting that such experience contributes to literacy development. Furthermore, those with instructional experience scored higher in knowledge of form and movement, although no such advantage was found in knowledge of the targeted muscle groups. This may indicate that although instruction can enhance the visible performance-related aspects of training, it may not sufficiently address a deeper anatomical understanding.

The significance of this study lies in its comprehensive depiction of training knowledge across sexes, age groups, and experiential backgrounds. Particularly noteworthy is the finding that knowledge regarding targeted muscle groups may be inadequately addressed in the current instructional practice. Moving forward, greater emphasis should be placed on instructional methods that not only improve the form and technique but also clarify the intended muscular targets of each exercise. Instructional strategies should encourage bidirectional communication and utilize clear, structured explanations supplemented by visual and sensory cues. Additionally, future studies should investigate the influence of training objectives, instructional quality, and frequency, as well as exploring how knowledge impacts behavior, using longitudinal and qualitative methodologies that account for psychological and sociocultural factors.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/sports13090322/s1, Table S1: Survey Items Assessing Knowledge of Targeted Muscle Groups and Exercise Form/Movement.

Author Contributions: Conceptualization, Y.K. and N.K.; methodology, Y.K., M.G. and N.K.; validation, Y.K. and N.K.; data curation, Y.K. and N.K.; formal analysis, Y.K., M.G., K.O., Y.M. and N.K.; investigation, N.K.; writing—original draft, Y.K. and N.K.; writing—review and editing, Y.K., Y.M., K.O. and N.K.; Project Administration, Y.K. and N.K.; Supervision, N.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The study protocol was reviewed and approved by the Research Ethics Committee of [Kyoto institute of Technology] (approval no: [2023-55] date: 2 October 2023).

Informed Consent Statement: Prior to answering the questionnaire, the participants were presented with an informed consent form on the initial page of the web-based survey. Only those who provided informed consent were permitted to participate.

Data Availability Statement: The data presented in this study are openly available in [Figshare] [https://doi.org/10.6084/m9.figshare.29484869].

Conflicts of Interest: Author Yoshiki Kobayashi is the CEO of Enjoydream Holdings Inc. He wasprimarily responsible for the development of the study design, data collection, data interpretation, and manuscript preparation, in consultation with the academic supervisor. Statistical assistance, editorial advice, and minor revisions were provided by the co-authors. The company had no influence on the data analysis or the decision to publish the findings. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Physical Responses During Matches of International Female Football Players with Cerebral Palsy According to Their Sport Classes

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Abstract: Background/Objectives: International-level competition opportunities have recently been introduced for female footballers with cerebral palsy (CP), highlighting a gap in the research on their physical performance during matches. The objectives of this study were (I) to describe the physical responses during the 2022 Women's World Cup of football players with cerebral palsy (CP) and (II) to analyze the differences in physical responses based on the players' sport class (i.e., FT1, FT2, and FT3). **Methods**: Physical responses were recorded using global positioning devices (GPS) during four official international matches. **Results**: The results showed that FT2 players covered more explosive distances than FT1 players ($p < 0.05$; ES = −0.82), and FT2 and FT3 players achieved higher maximum velocities than FT1 players ($p < 0.01$; ES = −1.16 and $p < 0.05$; ES = −1.41, respectively). Furthermore, FT2 players performed more accelerations ($p < 0.05$; ES = −0.82 to −1.01) and decelerations ($p < 0.01$; ES = −1.00) in the mid–high intensity zones than FT1 players. **Conclusions**: While the greater impairment of FT1 players may have influenced their lower physical responses in competition compared to FT2 and FT3 players, the absence of differences between FT2 and FT3 classes is a novel aspect that requires further scientific investigation.

Keywords: soccer; women; brain impairment; match load; Paralympics; para sport

1. Introduction

One of the main missions of the International Paralympic Committee (IPC) is to promote social inclusion by providing opportunities for sports participation for individuals with disabilities, from amateur to elite levels [1]. Particularly, in the field of Para sports such as cerebral palsy (CP) football, the International Federation of Cerebral Palsy Football (IFCPF) has recently taken on the responsibility of promoting equality among para-athletes

with the eligible impairments of spastic hypertonia, ataxia, and dyskinesia [2]. This commitment aims to ensure inclusivity regardless of gender, ethnic origin, faith, or culture, focusing on footballers with motor problems due to CP or related underlying health conditions [2]. CP football is a widely practiced team Para sport with both men's and women's divisions. However, almost all of its international tournaments and scientific research have focused on the male modality. Nevertheless, female CP football has been growing exponentially as a competitive sport in recent years across all levels [3]. Specifically, the growth of the modality has been a collaborative effort, marked by the inception of a national championships in 2017 and progressing towards the inaugural IFCPF World Cup 2022 in Salou, Spain.

From a scientific standpoint, to understand the sports discipline and adequately prepare female football players with CP for optimal performance, one of the primary areas of study should be the competition itself [4–6]. In the case of male CP football, competition has been analyzed from various perspectives, such as examining the physical responses of the players [7–9], their physiological responses [10], and even the technical and tactical actions through observational match analyses [11]. However, to date, no research has been addressing the competition element in female CP football, creating a significant gap in the scientific literature, especially regarding the differences in female players compared to their male counterparts concerning the size of the field of play (female: 40 $\times$ 27 m vs. male: 70 $\times$ 50 m), the number of players (female: five-a-side vs. male: seven-a-side) and the duration of an official match (female: two halves of 25 min plus 10 min of rest time vs. male: two halves of 30 min plus 15 min of rest time). In this sense, the external physical demands, as well as the fatigue and tactical behavior of both conventional football players and football players with CP, vary depending on the individual playing space and playing time [10,12]. In this regard, this study would be the first to analyze the physical responses of female football players with CP in competition, which could identify the specific demands of the game. This knowledge could be crucial for periodizing recovery strategies and adjusting weekly training loads in this population of para-athletes. Additionally, it could provide the classifiers with a better comprehension of the game for the classification process of female footballers with CP, who play with a different pitch size (smaller) and number of players (lower) in the line-up compared with their male counterparts.

On the other hand, due to the significant role of classification in Para sports [13], the study of physical responses during football matches based on sport class has also gained particular scientific relevance in recent years [9,14]. Particularly, in male CP football, it has been noted that the physical responses of players during competition vary depending on the sport class (i.e., at the beginning classified as FT5-FT8 and currently as FT1-FT3) [8,9]. Previous studies have indicated that male players in the FT2 and FT3 sport classes cover distances at higher intensities and achieve a higher maximum velocity compared to players in the FT1 class, who present a higher severity of the impairments [9]. Furthermore, players in FT3 also perform more accelerations and decelerations during competition compared to players in the FT1 and FT2 classes [7]. This scientific knowledge has contributed to modifying and enhancing the sport classification processes based on the scientific evidence [2,13,15]. Although in recent years, the scientific literature has focused on analyzing differences in physical responses during competition in male football players with CP [7–9], there is also a lack of knowledge regarding the physical responses of female footballers, considering the differences in the game compared with male CP football, but also whether female footballers' performances differ based on the sport classes of the players.

Given the significance of advancing scientific knowledge on competition in female CP football to align with the objectives established by the IPC and the IFCPF [1,16], conducting

research on this team Para sport modality is essential. Therefore, the main objectives of this study were (i) to describe the physical responses of female football players with CP during their first international-level competition and (ii) to analyze the differences in their physical responses based on the sport classes of the players (i.e., FT1, FT2, and FT3). Considering that differences in physical responses among male football players with CP based on the sport class have been previously observed [9], we hypothesized that differences in physical responses will also exist among female football players with CP, because of the level of impairment that is expected for each sport class.

2. Materials and Methods

2.1. Participants

Thirty-five international-level [17] female football players with CP (24.9 ± 8.3 years; 163.5 ± 7.0 cm; 59.0 ± 13.7 kg; 22.2 ± 3.5 kg·m^{-2}) from top five national teams that competed in the International Federation of CP Football (IFCPF) 2022 World Cup (Salou, Spain) were included, representing nearly (77.78%) all international players who were active in this team Para sport when the study took place. All players trained 2–3 days per week and had an average of 4.76 ± 4.26 years. of enrollment in a national team program. The inclusion criteria for study participation included having a valid IFCPF license, being selected by their country/national team, competing internationally in the 2022 IFCPF World Cup (Salou, Spain), and regularly playing as a field player. The exclusion criteria were any type of injury in the three months prior to data collection or regular play as a goalkeeper, due to their specific role during the match. Participants were grouped based on their sport class into FT1 (n = 12; 19 individual observations; 27.9 ± 10.6 years.; 161.6 ± 7.4 cm; 54.0 ± 10.1 kg; 20.5 ± kg·m^{-2}), FT2 (n = 19; 25 individual observations; 22.6 ± 6.0 years.; 164.8 ± 6.5 cm; 61.5 ± 14.8 kg; 22.5 ± 4.3 kg·m^{-2}), and FT3 (n = 4; 4 individual observations; 25.5 ± 4.8 years.; 165.0 ± 7.9 cm; 67.6 ± 17.1 kg; 24.5 ± 4.0 kg·m^{-2}). Participants were informed about the study procedures, could withdraw at any time, and were aware of the study risks before signing an institutionally approved informed consent document to participate. All procedures in this study were approved by the Ethics Committee of Miguel Hernández University (reference number DPS.RRV.03.17).

2.2. Procedures

Physical responses were recorded during official matches of the international competition (n = 35 players, 4 official matches, and 48 individual observations—i.e., physical responses monitored in a single game by one player—range = 1–3 matches per player). All variables were normalized based on the time played by each player in each match [9], except for the maximum velocity and maximum acceleration and deceleration variables (due to them representing absolute measures that are independent of playing time). All analyzed official matches were played five-a-side in the same sports facilities, using an artificial turf field of 40 × 27 m. Each match's duration was 50 min of regular time (divided into two halves of 25 min) [18]. There was no extra time in any of the analyzed matches. The mean playing time for all players was 31.0 ± 15.4 min (range = 2.0–57.0 min).

2.3. Physical Variables

The physical responses of the football players were recorded during the matches with WIMU PRO devices (RealTrack Systems, Almería, Spain) using Global Positioning System (GPS) technology, operating at a sampling frequency of 10 Hz. This equipment and its measurements are valid and reliable using GPS for time–motion analyses in football [19] and were awarded with the FIFA Quality Performance certificate. It should be noted that these

devices also had been used previously for measuring the physical responses of football players with CP [20]. Participants wore a vest, and the device was inserted on a vertical position between the players' shoulder blades into a specially designed harness, placed before the warm-up for each match. Before the start of each match, players underwent a 20–25 min warm-up with their team, including running, progressive sprints, and stretching. These warm-up data were not included in the study analysis. Data from the half-time interval between the two halves of the match (i.e., 15 min) were also excluded from the analysis. The records were downloaded using the SPRO software (version 983, RealTrack Systems, Almería, Spain) after the end of each match. The total distance (TD) ($m \cdot min^{-1}$) [7,9], explosive distance (ED) (total distance traveled with an acceleration greater than 1.12 $m \cdot s^{-2}$) ($m \cdot min^{-1}$) [20], maximum velocity achieved (Vel_{max}), distance ($m \cdot min^{-1}$) covered at different intensities [7] (walking: <6.0 $km \cdot h^{-1}$; jogging: 6.01–12.0 $km \cdot h^{-1}$; low-intensity running (LIR): 12.01–18.0 $km \cdot h^{-1}$; medium-intensity running (MIR): 18.01–21.0 $km \cdot h^{-1}$; high-intensity running (HIR): 21.01–24.0 $km \cdot h^{-1}$; and sprinting: 24.01–50.0 $km \cdot h^{-1}$), total number of accelerations (Acc) and decelerations (Dec) ($n \cdot min^{-1}$), maximum accelerations (Acc_{max}) and decelerations (Dec_{max}) reached ($m \cdot s^{-2}$) [7], and distances covered at different accelerations (Z1: 0/1 $m \cdot s^{-2}$; Z2: 1/2 $m \cdot s^{-2}$; Z3: 2/3 $m \cdot s^{-2}$; Z4: >3 $m \cdot s-^{2}$) and decelerations [7,9] (Z1: 0/−1 $m \cdot s^{-2}$; Z2: −1/−2 $m \cdot s^{-2}$; Z3: −2/−3 $m \cdot s^{-2}$; Z4: >−3 $m \cdot s^{-2}$) were calculated from the GPS-derived data. The player load (PL) was calculated as a vector magnitude representing the sum of accelerations recorded in the anteroposterior, mediolateral, and vertical planes [21].

2.4. Statistical Analysis

Results are presented as mean and standard deviation (SD). The Kolmogorov–Smirnov and Levene tests were applied to assess the data normality and homogeneity of variances, respectively. Parametric statistics were used for examined variables with a normal distribution of data and equal variances. However, non-parametric statistics were employed for MIR and HIR variables of distances covered at different speeds and zones 3 and 4 for accelerations and decelerations. To analyze differences between the FT1, FT2, and FT3 groups, a one-way analysis of variance (ANOVA) with Bonferroni post hoc comparison was used for variables with a normal distribution. For variables without a normal distribution, the non-parametric Kruskal–Wallis Test with Holm post hoc comparison was applied. The effect size (ES) was calculated using Cohen's d [22], with values above 0.8, between 0.8 and 0.5, between 0.5 and 0.2, and below 0.2 considered large, moderate, small, and trivial, respectively [22]. Data were analyzed using the JASP software for Windows (version 0.16, University of Amsterdam, Amsterdam, The Netherlands). Statistical significance was set at $p < 0.05$.

3. Results

Table 1 presents the results for the total distance covered, explosive distance (total distance covered with an acceleration greater than 1.12 $m \cdot s^{-2}$), maximum velocity achieved, and distance covered at different intensities during matches for all the female players with CP, as well as differences based on their sport classes. The results indicate that FT2 players covered a greater explosive distance ($p < 0.05$; ES = −0.82; large) and achieved a higher maximum velocity than FT1 players ($p < 0.01$; ES = −1.16; large). Additionally, FT3 players reached a higher maximum velocity than FT1 players ($p < 0.05$; ES = −1.41; large). No significant differences were observed in any analyzed variable between the FT2 and FT3 sport classes.

Table 2 presents the results for total accelerations and decelerations and maximum accelerations and decelerations, categorized into the different intensity zones, as well as the PL for the entire group of players, along with differences between sport classes. The study results indicate that FT2 players perform more accelerations in Z3 ($p < 0.05$; ES = −0.82; large) and Z4 ($p < 0.01$; ES = −1.01; large), and decelerations in Z3 ($p < 0.01$; ES = −1.00; large) than FT1 players. No significant differences were observed for any of the variables between FT1 and FT3 or between FT2 and FT3 players.

Table 1. Physical response variables related to the total distance covered, maximum velocity achieved, and distance covered at different intensities during football matches by female players with cerebral palsy.

	Total Sample (48 Observations)	FT1	FT2	FT3	Pairwise Comparisons		
					FT1 vs. FT2 ES	FT1 vs. FT3 ES	FT2 vs. FT3 ES
TD ($m \cdot min^{-1}$)	66.96 ± 13.35	65.68 ± 18.04	67.04 ± 9.47	72.52 ± 8.42	−0.10	−0.51	−0.41
Vel_{max} ($km \cdot h^{-1}$)	17.10 ± 2.28	15.66 ± 1.79	17.97 ± 2.14	18.48 ± 1.97	−1.16 **	−1.41 *	−0.26
ED ($m \cdot min^{-1}$)	5.23 ± 1.88	4.35 ± 1.37	5.82 ± 2.02	5.79 ± 1.89	−0.82 *	−0.81	0.02
Distance intensities ($m \cdot min^{-1}$)							
Walking (<6 $km \cdot h^{-1}$)	38.53 ± 6.82	40.41 ± 9.86	37.30 ± 3.23	37.30 ± 4.91	0.46	0.46	0.00
Jogging (6.01–12 $km \cdot h^{-1}$)	23.18 ± 8.46	22.18 ± 9.98	23.15 ± 7.26	28.13 ± 7.93	−0.11	−0.70	−0.59
LIR (12.01–18 $km \cdot h^{-1}$)	7.14 ± 4.73	6.03 ± 5.34	5.03 ± 4.43	6.83 ± 2.78	−0.42	−0.17	0.26
MIR (18.01–21 $km \cdot h^{-1}$)	0.17 ± 0.32	0.05 ± 0.14	0.25 ± 0.40	0.25 ± 0.30	−0.63	−0.62	0.00
HIR (21.01–24 $km \cdot h^{-1}$)	0.02 ± 0.07	0.00 ± 0.00	0.03 ± 0.09	0.01 ± 0.03	−0.53	−0.23	0.30
Sprinting (24.01–50 $km \cdot h^{-1}$)	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00	0.00	0.00

FT1 = sport class 1; FT2 = sport class 2; FT3 = sport class 3; ES = effect size; TD = total distance covered; Vel_{max} = maximum velocity achieved; ED = explosive distance; LIR = low-intensity running; MIR = moderate-intensity running; HIR = high-intensity running. Significant differences between sport classes: * $p < 0.05$, ** $p < 0.01$.

Table 2. Accelerations and decelerations recorded for the entire group and differences between sport classes during official matches by female players with cerebral palsy.

	Total Sample (48 Observations)	FT1	FT2	FT3	Pairwise Comparisons		
					FT1 vs. FT2 ES	FT1 vs. FT3 ES	FT2 vs. FT3 ES
Acc ($n \cdot min^{-1}$)	33.39 ± 5.46	35.06 ± 7.69	32.78 ± 2.87	29.21 ± 1.37	0.43	1.10	0.67
Dec ($n \cdot min^{-1}$)	23.72 ± 7.16	26.75 ± 5.96	20.72 ± 7.41	22.05 ± 8.08	0.89	0.70	−0.20
Acc_{max} ($m \cdot s^{-2}$)	4.69 ± 1.84	4.60 ± 1.80	4.78 ± 1.94	4.60 ± 1.76	−0.90	0.01	0.10
Dec_{max} ($m \cdot s^{-2}$)	−5.55 ± 2.34	−5.52 ± 2.24	−5.70 ± 2.49	−4.75 ± 2.28	0.08	−0.33	−0.40
PL ($AU \cdot min^{-1}$)	0.76 ± 0.50	0.63 ± 0.48	0.82 ± 0.53	1.03 ± 0.32	−0.38	−0.81	−0.42
Acc/Dec Zones ($n \cdot min^{-1}$)							
Acc Z1 (0/1 $m \cdot s^{-2}$)	17.46 ± 3.60	18.25 ± 5.19	16.89 ± 1.89	17.27 ± 2.43	0.38	0.27	−0.10
Acc Z2 (1/2 $m \cdot s^{-2}$)	12.58 ± 3.88	12.60 ± 4.22	12.64 ± 3.94	12.08 ± 2.08	−0.01	0.13	0.14
Acc Z3 (2/3 $m \cdot s^{-2}$)	4.41 ± 2.08	3.40 ± 1.39	4.98 ± 2.05	5.60 ± 3.37	−0.82 *	−1.14	−0.30
Acc Z4 (>3 $m \cdot s^{-2}$)	0.61 ± 0.81	0.15 ± 0.25	0.89 ± 0.95	1.07 ± 0.67	−1.01 **	−1.26	−0.25
Dec Z1 (0/−1 $m \cdot s^{-2}$)	17.52 ± 3.67	18.12 ± 5.22	16.79 ± 1.97	19.27 ± 2.33	0.37	−0.32	−0.60
Dec Z2 (−1/−2 $m \cdot s^{-2}$)	10.81 ± 3.05	10.86 ± 3.35	10.45 ± 2.60	12.87 ± 3.81	0.13	−0.66	−0.80
Dec Z3 (−2/−3 $m \cdot s^{-2}$)	3.72 ± 1.64	2.86 ± 1.20	4.37 ± 1.75	3.81 ± 0.87	−1.00 **	−0.60	0.37
Dec Z4 (>−3 $m \cdot s^{-2}$)	0.90 ± 0.94	0.54 ± 0.61	1.15 ± 1.07	1.07 ± 1.10	−0.66	−0.58	0.08

FT1 = sport class 1; FT2 = sport class 2; FT3 = sport class 3; ES = effect size; Acc = total accelerations; Dec = total decelerations; Acc_{max} = maximum acceleration; Dec_{max} = maximum deceleration; Acc/Dec Zones = zones of accelerations and decelerations at different intensities; Acc Z1 = accelerations between 0 and 1 $m \cdot s^{-2}$; Acc Z2 = accelerations between 1 and 2 $m \cdot s^{-2}$; Acc Z3 = accelerations between 2 and 3 $m \cdot s^{-2}$; Acc Z4 = accelerations > 3 $m \cdot s^{-2}$; Dec Z1 = decelerations between 0 and −1 $m \cdot s^{-2}$; Dec Z2 = decelerations between −1 and −2 $m \cdot s^{-2}$; Dec Z3 = decelerations between −2 and −3 $m \cdot s^{-2}$; Dec Z4 = decelerations < −3 $m \cdot s^{-2}$; PL = player load. Significant differences between sport classes: * $p < 0.05$, ** $p < 0.01$.

4. Discussion

The main objective of this study was to compare the physical responses of female football players with CP based on their sport class (i.e., FT1, FT2, and FT3) during the first international-level competition held for this group at the 2022 IFCPF World Cup. Despite exhaustive analysis of physical responses in official matches in male CP football in recent years [7–9], this is the first study to examine the physical responses during competition in female football players with CP. The main findings of this study showed that FT2 and FT3

players achieved higher maximum velocities than FT1 players. Additionally, FT2 players covered more explosive distances than FT1 players. Similarly, FT2 players performed more accelerations in Z3 and Z4 and more decelerations in Z3 than FT1 players. However, no significant differences were found in physical responses between FT2 and FT3 players. Understanding the physical responses in competition and the differences between sport classes in female CP football would provide insights into the workloads of this sport modality and establish reference values for physical conditioning specialists to prepare female players for competition. Moreover, this study could also assist classification panels during the observation assessment processes during the game.

Our results do not align with a previous study conducted with male footballers with CP [9], which involved 42 players from different national teams during the 2016 World Championship. In that study, no significant differences were found between sport classes in maximum velocity or distances covered at different intensities. However, the results of this study partially coincide with those obtained in a study by Reina et al. [14], which showed significant differences in maximum velocities between the FT1 and FT2 classes and FT1 and FT3 players, walking distances between FT1 and FT2 players and FT1 and FT3 players, low-intensity distances between FT1 and FT3 players, and sprint distances between FT1 and FT2 players and FT1 and FT3 players. Similarly to this study, Reina et al. [14] found no significant differences in these variables between FT2 and FT3 players. These results also align with a previous study by Reina et al. [8], where significant differences were found in maximum velocities between FT1 and FT3 players and in sprint intensity distances (>18 $km \cdot h^{-1}$) between FT1 and FT3 players. In contrast to the present study, Reina et al. [14] found significant differences between the FT2 and FT3 classes in the maximum velocity achieved. A smaller field size and the smaller number of players could explain the difference in results compared to the results for men, as female football players with CP may adopt different tactical roles. In this regard, in the male format (seven-a-side, field dimensions of 70 $\times$ 50 m), the individual interaction space is 250 m^2, whereas in the female CP football format (five-a-side, field dimensions of 40 $\times$ 27 m), the individual interaction space is 108 m^2. The fact that the individual interaction space is significantly smaller could have influenced the ability of female players to reach their maximum physical potential in distances covered at medium-to-high intensities. The fact that FT1 players in this study obtained lower values for explosive distance or maximum velocity than FT2 and FT3 players can be partially explained by the greater physical impairment that FT1 players have, resulting in greater limitations in the range and coordination of lower limb movements [23,24]. These players may also have lower functional capacity due to their impairment [25], limiting their ability to achieve higher maximum velocities or cover more explosive distances in competition. However, the results of this study did not show significant differences between sport classes in the distances covered at medium and high speeds. Possibly, the absence of differences between sport classes in these variables is due to female footballers with CP rarely reaching these intensities in matches, but also, the smaller field of play may also explain these findings. The distances covered at moderate, high, and sprinting intensities by players from all classes were close to zero (total observations: MIR = 0.17 $\pm$ 0.32 $m \cdot min^{-1}$; HIR = 0.02 $\pm$ 0.07 $m \cdot min^{-1}$; and sprinting = 0.00 $\pm$ 0.00 $m \cdot min^{-1}$). These results contrast with those obtained for female players in conventional football, where they cover greater distances at medium or high intensities [26–28]. These results highlight that during competition, female football players with CP rarely reach speeds exceeding 18 $km \cdot h^{-1}$. More studies are needed to determine whether the reasons for not covering distances at these speeds are due to impairment, training levels, or other factors that are inherent to the competition format (i.e., the field

size, individual interaction space, number of players during the game, or duration of an official game). However, considering that significant differences were observed between the sport classes in maximum velocity and explosive distance, the results of this study can be relevant, indicating that FT1 players have more activity limitations compared to FT2 and FT3 players in these variables. In addition, it could be considered that the defined zones may not be the most correct zones for female players with CP and that they may be used differently than the ones used for male players with CP considering the differences between both CP football modalities.

On the other hand, the abilities to accelerate and decelerate have been defined as important variables for sports performance [29] and have been studied in various research studies on male CP football to understand the neuromuscular demands of this Para sport [8,9]. Furthermore, it has been described that the specific demands of speed changes in competition, based on sport classes and the type of coordination problems (including levels of spastic hypertonia), have implications for the training of CP football teams [7,30]. In this regard, physical performance in CP football is determined by the player's ability to perform short, fast, and specific actions (such as accelerating, decelerating, sprinting, or changing direction), as well as to withstand repetitions of these actions [20]. However, up to this point, no research has analyzed the physical capabilities of accelerations and decelerations that female football players with CP achieve in an international-level competition. Novelly, in the present study, FT2 class players performed more accelerations in Z3 and Z4 and more decelerations in Z3 than FT1 class players. However, no significant differences were observed in accelerations and decelerations at any intensity (Z1-Z4) between FT1 and FT3 players or between FT2 and FT3 players. The differences found in accelerations and decelerations between FT1 and FT2 players may be explained by the differences in the impact of the impairment [30] of players in both sport classes. However, the absence of differences between FT1 and FT3 players or between FT2 and FT3 does not align with the results obtained for male footballers with CP. In reports with male football players with CP [8,9,14], it was found that overall, FT3 players performed more high-intensity accelerations (>2.78 $m \cdot s^{-2}$) than those in FT1, with a moderate to large effect size ($p < 0.05$; ES range = 0.50–1.18). Furthermore, it has also been reported that FT3 players performed more high-intensity accelerations than FT2 players ($p < 0.05$; ES range = 0.73–0.86; moderate-to-large) [8,9]. Reina et al. [8] also found that FT3 players performed a greater number of moderate decelerations (-1.00 to -2.78 $m \cdot s^{-2}$) than FT1 ($p < 0.05$; ES = 0.73) and FT2 players ($p < 0.05$; ES = 0.69). Considering that the sport classification is determined by the players' impairments, the absence of differences in accelerations and decelerations between FT1 and FT3 players and between FT2 and FT3 players is surprising. It also seems that female players with CP accelerate and decelerate at low intensities. Possibly, the lack of differences between these classes could be due to the different sample sizes in the various classes, especially in the FT3 group (n = 4 players). The fact that the participation of FT3 players is limited by the competition regulations (i.e., no more than one FT3 and at least one FT1 player in the field of play) [18] has not allowed for the inclusion of more players from this sport class, and this aspect may have influenced the obtained results. Another explanation could be the recent development of female CP football, where the level of training and competitive experiences is lower compared to male footballers with CP and where FT3 players are relevant players for tactics and strategy. Taking into account that the abilities to accelerate and decelerate are useful for assessing activity limitations in male footballers with neurological impairments [8], the understanding of the demands of short-duration, high-intensity actions (such as accelerations and decelerations) in their female counterparts would provide relevant information to understand the type of activity

and demands in female CP football competition. A different trend is observed compared to male CP football, where there are more FT2 classes and a higher number of FT3 players, while FT1 remains the minority. The limited significant differences between FT2 and FT3 players could be attributed to their higher functional ability, combined with a smaller pitch size and the specific constraints of the modality (e.g., five-a-side game), which may limit variations in physical variables. What stands out in this population is that there are more women with higher levels of impairment competing, reflected in the large number of competitors in this sport class. This is noteworthy, because one might expect teams to seek more borderline athletes or those with greater functionality as the sport develops and becomes more competitive. However, this knowledge could contribute to designing specific and effective training programs for players, so more studies with larger sample sizes, especially from FT3 players, are needed to understand whether there are differences between the FT1 and FT2 classes compared to the FT3 class. Also, it will be interesting to conduct longitudinal studies to explore the performance improvements of female football players with CP with the development of the discipline and the inclusion of new national teams at international-level competitions.

Although the results of this research provide practical and novel information for both physical trainers and classification teams regarding the physical performance in competition of female footballers with CP, it is necessary to consider certain study limitations. First, the participant sample size was small due to data being obtained at the 2022 World Cup, but it is worth mentioning that an international-level group of the top five world class national teams was tested. Particularly, the limited representation of players in the FT3 category constitutes a significant practical constraint that could have affected the obtained results, although competition rules limit each team to only having one FT3 player in the field of play [18]. Therefore, although the analysis was carried out with four FT3 players, they represented a high percentage of the total number of players in that sport class playing female CP football when the study was completed. However, future research should aim to replicate the study with a larger sample as women's participation in international championships continues to increase. On the other hand, the disparity in sample size between players of different sport classes (a practical limitation due to the different rules for the game for female and male CP football) could introduce potential biases in interpreting the results. Another limitation is the lack of analysis of physiological responses and a match observational analysis. Considering that there is currently a limitation imposed by the IFCPF competition regulations on the use of heart rate wristbands, a possible solution could be to record these variables during simulated matches or request the necessary permissions from the relevant governing body to collect these data during official competitions. These suggestions will allow for a more complete and thorough understanding of the specific competitive demands of female CP football, providing deeper insights into the competition. Furthermore, considering that this pioneering research addresses female CP football, there is a need for additional studies to delve into the association between performance in functional and match tests (i.e., balance, coordination, change in direction ability tests, etc.) and consider contextual factors such as the type of tournament (i.e., national or international) and environmental conditions (i.e., sea level or altitude).

5. Conclusions

The results of this study seem to indicate that the greater impairment of FT1 players may have influenced their lower competition responses compared to FT2 and FT3 players. However, despite the fact that the impairment of FT2 players is bigger than that of FT3 class players, the results obtained in this study found no significant differences in any of the

competition-related physical response variables between FT2 and FT3 players. Therefore, it seems necessary to conduct more studies with larger sample sizes that analyze the physical responses of female football players with CP during matches, focusing specifically on differences between the FT2 and FT3 (i.e., minimal impairment) sport classes. On the other hand, a differentiating finding between conventional female football and male CP football was that female football players with CP did not reach speeds higher than 18 $km \cdot h^{-1}$, and the distance at medium and high speeds was very low.

Author Contributions: Conceptualization, O.B., J.Y. and D.C.; methodology, O.B., J.Y. and D.C.; formal analysis, O.B.; data curation, M.H.; writing—original draft preparation, O.B., J.Y. and D.C.; writing—review and editing, R.R., A.I., M.H. and I.E.; project administration, J.Y. and D.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research has been funded through the University-Company-Society 2023 Project convened by the University of the Basque Country (UPV/EHU) entitled "Muévete 2.0: análisis de la capacidad funcional de personas con discapacidad (code US23/14)" and requested in collaboration with the Fundación GaituzSport Fundazioa.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by Ethics Committee of Miguel Hernández University (reference number DPS.RRV.03.17, approval date: October 2017) for studies involving humans.

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

Data Availability Statement: The data files that support the findings of this study are available from the corresponding author (DC) upon reasonable request.

Acknowledgments: The authors would like to thank the collaboration of the International Federation of Cerebral Palsy Football.

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

Abbreviations

The following abbreviations are used in this manuscript:

IPC	International Paralympic Committee
CP	Cerebral palsy
IFCPF	International Federation of Cerebral Palsy Football
FT	Sport class
Vel_{max}	Maximum velocity achieved
Acc_{max}	Maximum acceleration achieved
Dec_{max}	Maximum deceleration achieved
GPS	Global Positioning System
TD	Total distance
ED	Explosive distance
MIR	Medium-intensity running
HIR	High-intensity running
Acc	Accelerations
Dec	Decelerations
PL	Player load
SD	Standard deviation
ES	Effect size

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ISBN 978-3-7258-8782-8