Research Topics

# Enhancing physical activity in women across the lifespan: evidence-based insights into quantification, intervention, outcomes, and limitations


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# Enhancing physical activity in women across the lifespan: evidence-based insights into quantification, intervention, outcomes, and limitations

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# Editorial: Enhancing physical activity in women across the lifespan: evidence-based insights into quantification, intervention, outcomes, and limitations

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**women, public health, sports performance, physical activity interventions, physical fitness, monitoring systems, injury treatment**

Editorial on the Research Topic
Enhancing physical activity in women across the lifespan: evidence-based insights into quantification, intervention, outcomes, and limitations

## 1 Introduction

Although sports and physical activity research has grown substantially over the past decades—with evidence from analyses of publications and citations demonstrating a marked increase in sports science over the last four decades, reflecting the growing recognition and importance of this field (1) — the research itself has predominantly focused on male participants, leaving a critical gap in our understanding of women's experiences. An analysis of publications indexed in Web of Science between 2014 and 2020 showed that 66% of study participants were men (8,253,236), whereas only 34% were women (4,254,445) ($p < .0001$), underscoring the persistent underrepresentation of women in sports and exercise science research (2). This imbalance constrains the development of knowledge regarding the unique physiological mechanisms, training loads, recovery patterns, and performance contexts specific to women (3). Addressing this gap is essential not only for advancing scientific understanding but also for informing practitioners, shaping effective interventions, and guiding policies that support women's health and performance. This collection directly addresses this gap by focusing on women's physical activity across different life stages and contexts, thereby expanding the evidence base that has historically been centered on men. Therefore, this Research Topic was created to further develop knowledge on women's physical activity across different life stages and to provide practical and theoretical insights that can contribute to science, policy, and practice.

## 2 Contribution to the field

The purpose of this Research Topic is to build a collection of new knowledge related to the effects of women's physical activity across different life stages and to provide practical and theoretical insights that can contribute to science, policy, and practice. The 11 contributions (one Study Protocol and ten Original Research articles, including five cross-sectional studies, four randomized controlled trials, and one case study) offer readers an opportunity to substantially advance their knowledge in this field. In total, the sample included 3,082 participants (2,869 women and 213 men) from 12 countries (Serbia, Bulgaria, Greece, Romania, North Macedonia, China, South Korea, Spain, Czechia, Ghana, Poland, and Italy), ranging in age from 14 to 85 years old.

The studies included in this Research Topic span a wide spectrum of methodological approaches, themes, and age groups, which allowed for several possible classifications and interpretations. Ultimately, we decided to structure them into three thematic categories—(1) Gender and social factors, (2) Interventions and training programs, and (3) Specific populations and risks—and to interpret them accordingly.

The first group comprised four studies that addressed gender and social factors (one Study Protocol and three cross-sectional studies). The findings highlight the following: the development of a reliable protocol enabling the systematic monitoring of gender equality and women's representation in sports and sports leadership, with the potential to contribute to reducing the gender gap (Kascelan et al.); the significant influence of the built environment on the physical activity and mental well-being of young women in the Balkans, suggesting that inclusive urban planning could be a key strategy for improving public health (Masoumi et al.); that gender stereotypes reduce the likelihood of engaging in physical activity, whereas breaking these stereotypes and fostering a supportive environment may enhance women's participation in exercise (Guo & Huang); and that single parents who meet the WHO physical activity guidelines report a significantly better quality of life, with effects particularly pronounced among women and older adults (Owusu-Sarpong et al.).

The second group consisted of four studies evaluating various interventions and training programs, all of them randomized controlled trials. Based on their results, it can be concluded: that a six-week social support program in the form of the Mindful Mothering Nursing Intervention reduced parenting stress and improved parenting efficacy among mothers with adverse childhood experiences (Cho & Shin); that a 12-week high-intensity interval training program improved executive functions in young sedentary women, although changes in IGF-1 were not significant (Jimenez-Roldán et al.); that a 12-week taekwondo program increased muscle mass, enhanced physical function, and contributed to favorable metabolic changes in older sedentary women (Park et al.); and that a 12-week program of standard and Nordic walking in postmenopausal women improved exercise tolerance and induced favorable changes in body composition, with Nordic walking providing greater benefits for aerobic capacity and functional performance (Knappova et al.).

The third group included three studies that focused on specific populations and highlighted unique challenges (one case study and two cross-sectional studies). The results demonstrated that during a 5-week fight camp, the chronic and rapid weight loss experienced by an elite female Muay Thai athlete reduced her strength and basal metabolism, strained her kidney function, and worsened her blood parameters, pointing to health risks and the Relative Energy Deficiency in Sport (RED-s) syndrome. This finding also highlights the importance of individualized and evidence-based weight management strategies to mitigate negative health outcomes and enhance athletic performance in combat sports (Bulínová et al.); that handgrip strength (HGS) was only weakly to moderately associated with functional abilities and gait speed in older women, and therefore HGS is not sufficient as a stand-alone indicator of functional capacity, whereas chair stand tests (30s-CS and 5-CS) emerged as more reliable predictors of slow gait (Muollo et al.); and that higher accumulation of visceral fat (measured by MRI) is significantly associated with increased liver mass and unfavorable lipid and metabolic profiles, even when body weight, BMI, and total body fat were within normal ranges—indicating that visceral fat may represent a hidden risk even in healthy, young, non-obese adults (Zhang et al.).

## 3 Conclusion

This special issue, with its 11 articles, confirms the well-established evidence of the benefits of gender-sensitive research on physical activity and its potential to improve women's health and quality of life (4, Kascelan et al.). It further provides concrete proposals in the form of a wide spectrum of practical tools: psychological and social support programs for mothers; protocols for systematically monitoring gender equality in sports; various forms of structured physical activity programs designed for young, older, and postmenopausal women; validated tests for assessing functional capacity and the risk of slow gait in older adults; and methods for the early detection of hidden metabolic risks through visceral fat analysis. These tools are intended to serve the purposes of diagnosis, and the prevention of specific conditions, problems, and phenomena, in addition to their treatment, correction, or at least mitigation. Importantly, the proposed tools have been tested, and practitioners will be able to apply them either fully or partially, with a high probability of predicting transformation or the desired outcome.

Ultimately, we believe that the information and practical recommendations presented here will serve as a stimulus for new research ideas and innovative solutions, bringing us closer to more effective gender-sensitive strategies for improving women's health and performance in the future. These strategies are part of the ongoing endeavor to, paraphrasing the title of this research topic, enhance physical activity in women across the lifespan.

## Author contributions

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# 25-Hydroxyvitamin D status does not affect energy metabolism among young, healthy, non-obese adults: a metabolic chamber study

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**Purpose:** here is a general consensus that an inverse relationship exists between vitamin D status and body mass index (BMI) in overweight and obese individuals, leading to the hypothesis that vitamin D deficiency may contribute to the development of unfavorable metabolic phenotypes. However, evidence from non-obese adults remains limited. This study measured energy metabolism in non-obese adults using a metabolic chamber and explored its association with vitamin D status.

**Methods:** Sixty-nine healthy adults (mean age = 22.8 years, mean BMI = 20.7 kg/m$^2$) participated in this cross-sectional study. Participants were categorized into vitamin D-deficient, insufficient, and sufficient groups based on the Chinese classification for total 25(OH)D levels (WS/T 677–2020). They performed typical daily activities in a metabolic chamber, where their baseline lipid profile, 24-hour energy expenditure, and substrate oxidation were measured.

**Results:** A two-way ANOVA (seasonality × 25(OH)D) revealed no statistically significant differences in total energy expenditure, resting energy expenditure, sleeping energy expenditure, walking energy expenditure, carbohydrate oxidation rate, or fat oxidation rate among the three groups ($p > 0.05$). These results remained consistent even after adjusting for fat-free mass. Although statistically significant correlations were found between 25(OH)D status and certain lipid profile markers (i.e., total cholesterol, high-density lipoprotein, and free fatty acid) ($p < 0.05$), these correlations were weak, with Pearson's correlation coefficients below 0.3.

**Conclusions:** Total 25(OH)D status does not affect energy metabolism in young, healthy, non-obese adults. Along with existing evidence, this suggests that low 25 (OH)D status is more likely a consequence of unfavorable metabolic phenotypes rather than a contributing factor.

**Clinical trial registration:** https://www.chictr.org.cn, identifier ChiCTR-IIR-17010604.

KEYWORDS

energy expenditure, lipid profile, oxidation rate, vitamin D, obesity, physical activity

# 1 Introduction

Vitamin D, a fat-soluble sterol compound and hormone precursor, plays a critical role in various physiological functions (1). Among these, its involvement in human energy metabolism has garnered significant attention over the past decade (2). Research has shown that vitamin D status is a positive predictor of resting energy expenditure in adults, independent of obesity or metabolic syndrome (3). This has led to the hypothesis that vitamin D insufficiency or deficiency may be an independent risk factor for unfavorable metabolic phenotypes such as obesity, type 2 diabetes, and dyslipidemia — primarily supported by observational studies (4). In the Framingham Heart Study, for example, vitamin D status was inversely associated with waist circumference and visceral adipose tissue in non-diabetic individuals (5). Similar associations have been observed across various populations, including obese adults (6), healthy children (7), and older adults (8). Given this body of evidence, vitamin D supplementation has been explored as a potential strategy to improve metabolic health. However, many intervention studies have not demonstrated a causal effect of vitamin D status on obesity metrics or weight loss (9, 10). Despite this, the prevalence of poor vitamin D status among individuals with metabolic diseases highlights the need for further research into the relationship between vitamin D and energy metabolism.

There are three main limitations in research on vitamin D's role in energy metabolism. First, while rodent models often provide valuable insights into human disease development and treatments, the effects of vitamin D metabolism on energy homeostasis differ significantly between animal and human studies (11). Given this limitation, more rigorously controlled experimental studies in humans are necessary. Second, most studies in this field rely on metabolic cart measurements to estimate whole-body energy metabolism (3, 12). Methodologically, metabolic cart-based assessments of energy expenditure and macronutrient oxidation, especially through short-term measurements, may yield inaccurate results (13). In contrast, metabolic chambers, which allow unrestricted human movement and locomotion, provide not only more accurate measurements but also a better representation of real-life energy metabolism. Yet, the high costs and demanding research conditions (e.g., 24-hour observation) associated with metabolic chambers pose significant challenges. To our knowledge, studies in this area using metabolic chambers are scarce. Given the sensitivity needed to detect small yet meaningful effects of vitamin D on physiological functions, more studies utilizing metabolic chambers are required. Third, vitamin D deficiency and essential mineral deficiencies in general are common worldwide (14), affecting not only obese populations but also healthy individuals. From a preventive medicine perspective, understanding vitamin D's role in energy metabolism among healthy individuals is of significant public health interest. In vitamin D-sufficient young adults, for example, additional vitamin D supplementation has been shown to have no effect on resting energy expenditure (12). As outlined above, due to the limited data from representative 24-hour energy metabolism studies, there are currently no conclusive guidelines to determine vitamin D requirements for metabolic health in the general population. Specifically, data on young individuals with vitamin D insufficiency or deficiency remain scarce.

Therefore, the purpose of this study was to explore the impact of vitamin D status, measured by 25-hydroxyvitamin D (25(OH)D), on energy expenditure and substrate oxidation in young, healthy, non-obese adults. To address the limitations of previous research, a metabolic chamber was utilized to measure energy metabolism over a 24-hour period during typical daily activities. The findings are expected to provide new insights into the effects of vitamin D status on metabolic health in the general population.

# 2 Methods

## 2.1 Study design

This trial (clinical registration: ChiCTR-IIR-17010604) was approved by the Ethics Committee of the Shanghai University of Sport (approval # 2015009). According to China's guidelines for vitamin D deficiency screening (Chinese Standard GB/T: WS/T 677–2020), vitamin D status is classified as follows: adequate (serum total 25(OH)D $\geq$ 50 nmol/L), insufficient (30 $\leq$ 25(OH)D < 50 nmol/L), and deficient (25(OH)D $< 30$ nmol/L). This study aimed to use a one-way ANOVA to examine the relationship between 25 (OH)D status and energy metabolism. Assuming a Cohen's d of 0.5, p-value of 0.05, and 80% power for F-tests, the minimum required sample size for statistical significance in this cross-sectional, three-group design was 14 participants per group.

Potential participants were recruited from the Shanghai University of Sport between March 2017 and October 2018. Eligibility criteria included: age between 18 and 30 years, body mass index (BMI) $\leq 25$ kg/m$^2$, and no use of medications or nutritional supplements (e.g., vitamin $B_2$, vitamin D, or weight-loss drugs) that could influence vitamin D status, energy metabolism, or lipid profile within the six months before the study. All participants provided written informed consent. A total of 69 students, most of whom were female, were recruited. Their general characteristics are presented in Table 1. Apart from differences in 25(OH)D status and maximal oxygen consumption, no significant differences were observed among the three groups.

## 2.2 Protocol

At least one week before the metabolic chamber test, participants completed a maximum oxygen consumption test using a cycle ergometer and the Cosmed K4b2 portable metabolic system (Cosmed, Inc., Rome, Italy). During the same visit, body composition was assessed using a dual-energy X-ray absorptiometry scanner (GE Lunar Prodigy, USA).

On the experimental day, blood samples were collected from participants at 7:30 AM by accredited nurses following a 12-hour overnight fast. After resting at room temperature for 20–30 minutes, the samples were centrifuged at 3000 rpm for 15 minutes at 4°C. The serum was then transferred to additive-free tubes and immediately stored at -80°C for further analysis. Serum 25(OH)D concentrations were measured using the 25-Hydroxy Vitamin D EIA (AC-57SF1, IDS Ltd), which has a sensitivity of 3.3 nmol/L and intra- and inter-assay coefficients of variation of 8.9% and 10.6%, respectively. Immunoreactive parathyroid hormone levels were determined using the EIA-4140 (DRG Inc.), with intra- and inter-assay coefficients of variation of 9.6%. Serum total cholesterol was measured using the cholesterol oxidase method.

Participants' 24-hour energy metabolism was measured in an indirect calorimetry chamber (Fuji High Accuracy Human Calorimeter, FHC-20S, Japan), which was maintained at 25°C with 50% humidity. Participants followed a structured activity protocol, as outlined in Table 2, from 10 AM on day 1 to 10 AM on day 2. Three meals were provided based on age and body mass, adhering to the estimated energy requirements outlined in the Chinese Dietary Reference Intakes (Chinese Standard GB/T: WS/T 578.1–2017). The macronutrient composition of the meals was standardized to provide 50–60% of total calories from carbohydrates, 20–30% from fat, and 15–20% from protein. Breakfast, lunch, and dinner accounted for 30%, 40%, and 30% of the total daily caloric intake, respectively. Using minute-by-minute data on oxygen consumption and carbon dioxide production, 24-hour energy expenditure was calculated with Weir's formula (15). The Frayn equation was applied to estimate carbohydrate and fat oxidation rates (16).

## 2.3 Statistics

The de-identified data supporting the conclusions of this study are deposited at Figshare (DOI: 10.6084/m9.figshare.27280311.v1). All statistical analyses were performed using R version 4.4.1 (Race for Your Life). Considering the seasonal effects on the body's vitamin D production (17), a two-way ANOVA, as illustrated in

TABLE 1 Demographics characteristics.

| Demographics | Serum 25(OH)D status | | | Pairwise comparison |
|---|---|---|---|---|
| | Deficiency | Insufficiency | Adequacy | |
| n (men) | 30 (3) | 25 <<(>>2<<)>> | 14 (3) | – |
| 25(OH)D (nmol·L$^{-1}$) | 22.1 ± 5.6 | 37.4 ± 4.1 | 57.1 ± 7.1 | $F$ = 200, $p < 0.001$ |
| Age (years) | 23.6 ± 2.0 | 22.3 ± 2.1 | 22.2 ± 2.5 | $F$ = 3.2, $p$ = 0.048 |
| Height (cm) | 161 ± 6 | 162 ± 8 | 166 ± 9 | $F$ = 2.9, $p$ = 0.063 |
| Body weight (kg) | 53.8 ± 6.1 | 54.4 ± 9.8 | 57.4 ± 7.5 | $F$ = 1.0, $p$ = 0.366 |
| BMI (kg·m$^2$) | 20.8 ± 1.7 | 20.5 ± 2.5 | 21.0 ± 2.4 | $F$ = 0.2, $p$ = 0.826 |
| Fat free mass (kg) | 36.1 (5.4) | 36.9 (3.9) | 38.4 (8.1) | $\chi 2$ = 1.5, $p$ = 0.461 |
| Fat (%) | 29.3 ± 6.3 | 28.5 ± 7.0 | 27.5 ± 7.4 | $F$ = 0.3, $p$ = 0.708 |
| Body surface area[a] | 1976 ± 179 | 1984 ± 248 | 2105 ± 270 | $F$ = 1.7, $p$ = 0.183 |
| $VO_{2max}$ (ml·kg$^{-1}$·min$^{-1}$) | 30.6 ± 5.1 | 34.2 ± 4.4 | 36.4 ± 6.1 | $F$ = 6.6, $p$ = 0.003 |
| Parathyroid hormone (pg·ml$^{-1}$) | 48.5 ± 16.8 | 58.3 ± 23.5 | 64.2 ± 29.5 | $F$ = 2.7, $p$ = 0.077 |

Data are expressed as mean ± standard deviation or median (interquartile range). [a]based on the Du Bois formula.

TABLE 2 Schedule of 2-day activities in the metabolic chamber.

| Day 1 | Activity of day 1 | 18:00 PM | Viewing smart phone at a desk |
|---|---|---|---|
| 9:30 AM | Enter chamber | 18:30 PM | Writing at a desk |
| 10:00 AM | Working on a laptop | 19:00 PM | listening to music |
| 11:00 AM | Doing a cervical and lumbar gymnastics | 19:30 PM | Reading at a desk |
| 11:30 AM | Viewing smart phone at a desk | 20:00 PM | Watching video |
| 12:00 PM | Lunch | 22:00 PM | Quietly resting on bed (rest metabolic rate) |
| 12:20 PM | Doing housework | 22:45 PM | Washing and ready to sleep |
| 12:30 PM | Midday break | 23:00 PM | Sleep |
| 13:30 PM | Listening to music | Day 2 | Activity of day 2 |
| 14:00 PM | Reading at a desk | 7:00 AM | Going to the bathroom |
| 14:30 PM | Writing at a desk | 7:15 AM | Resting on bed (basal metabolic rate) |
| 15:00 PM | Doing a cervical and lumbar gymnastics | 8:00 AM | Breakfast |
| 15:30 PM | Watching video | 8:30 AM | Viewing smart phone at a desk |
| 16:30 PM | Treadmill walking at 3.2 km/h | 9:00 AM | Treadmill walking at 5.6 km/h |
| 16:40 PM | Working on a laptop | 9:30 AM | Reading at a desk |
| 17:40 PM | Diner | 10:00 AM | Energy metabolism collection ends |

Figure 1, was used to examine the relationship between 25(OH)D status and energy metabolism. Additionally, Pearson's correlation coefficient or Spearman's rank correlation coefficient was employed to assess the relationship between 25(OH)D status and the lipid profile. To address asymmetry due to differing measurement units, log transformations were applied before conducting the correlation analysis. Statistical significance was set at the 5% level.

# 3 Results

Based on the two-way ANOVA, no significant interaction effect was detected, with F-test values ranging from 0.22 to 2.52 and p-values between 0.22 and 0.95. Therefore, we can conclude that seasonality did not influence the primary outcomes of this study. A one-way ANOVA was used to assess the main effect of 25(OH)D

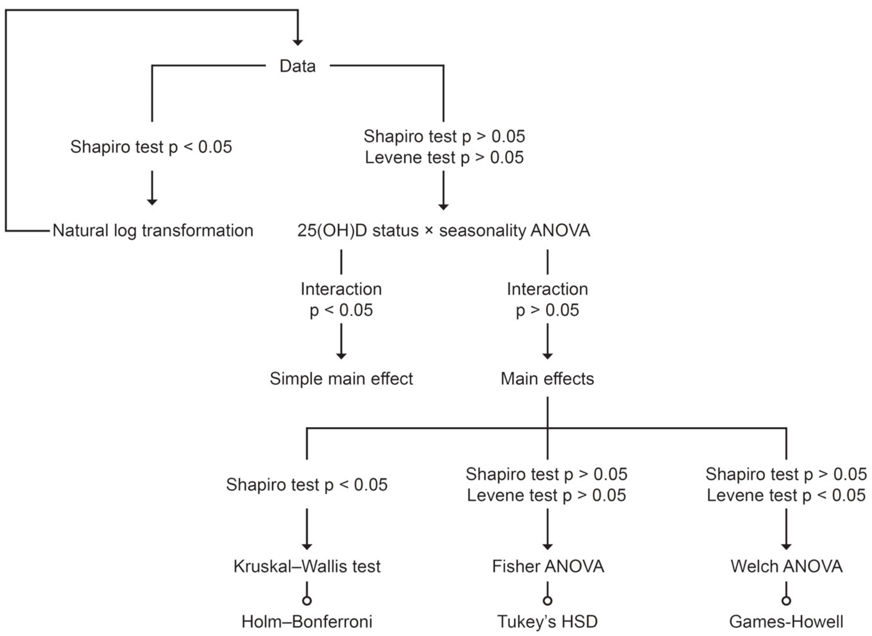


FIGURE 1
Decision tree of two-way ANOVA.

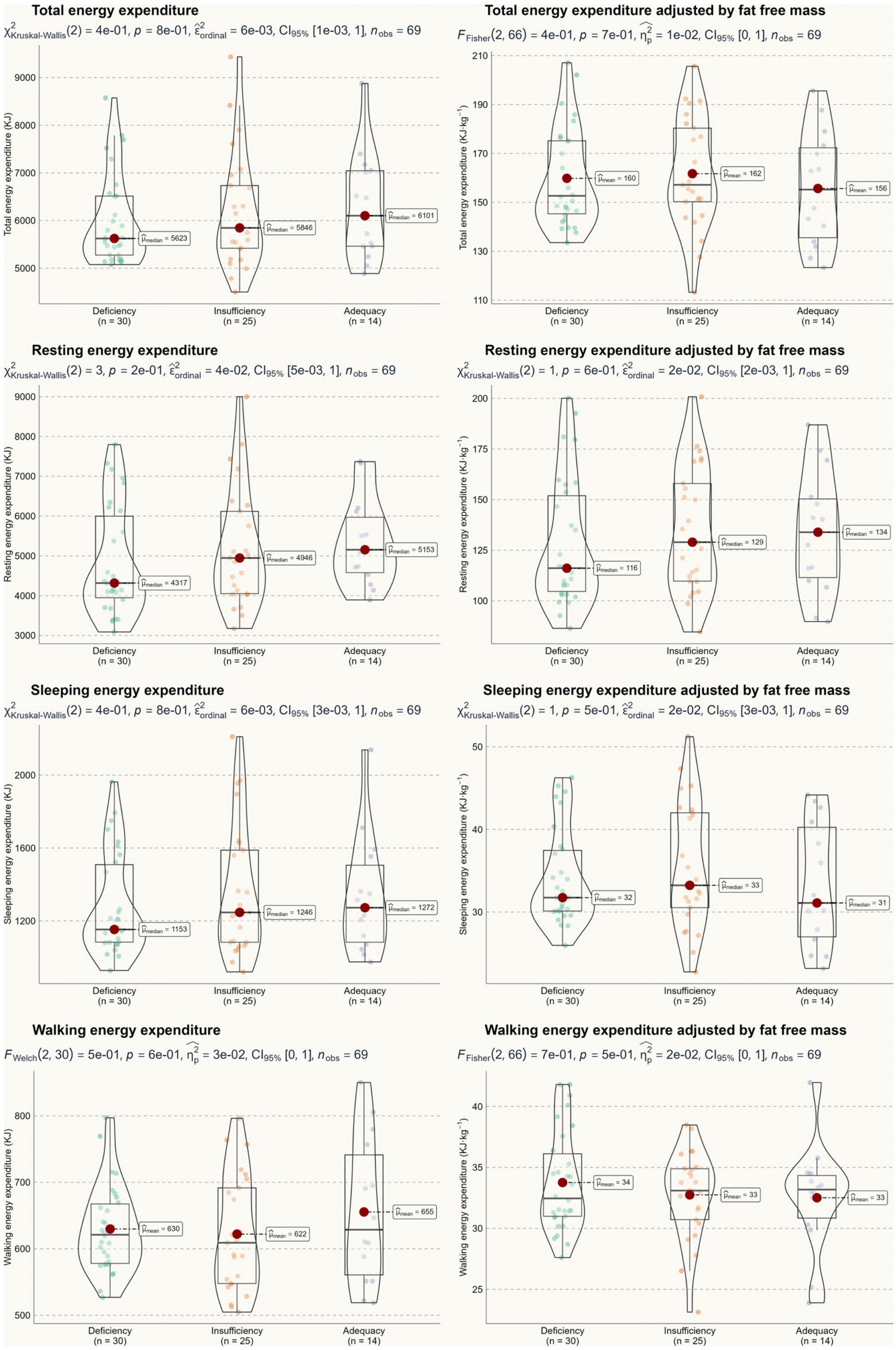


FIGURE 2
Energy metabolism by serum 25(OH)D status.

status, and Figures 2 and 3 illustrate energy metabolism across the three groups. In summary, neither energy expenditure nor substrate oxidation rates were significantly affected by 25(OH)D status, even after adjusting energy metabolism for fat-free mass (as shown in Figure 2), body weight (not shown here), or muscle mass (not shown here). The main effect of seasonality is detailed in Table 3, where participants tested in the spring exhibited significantly higher values across most energy metabolism metrics.

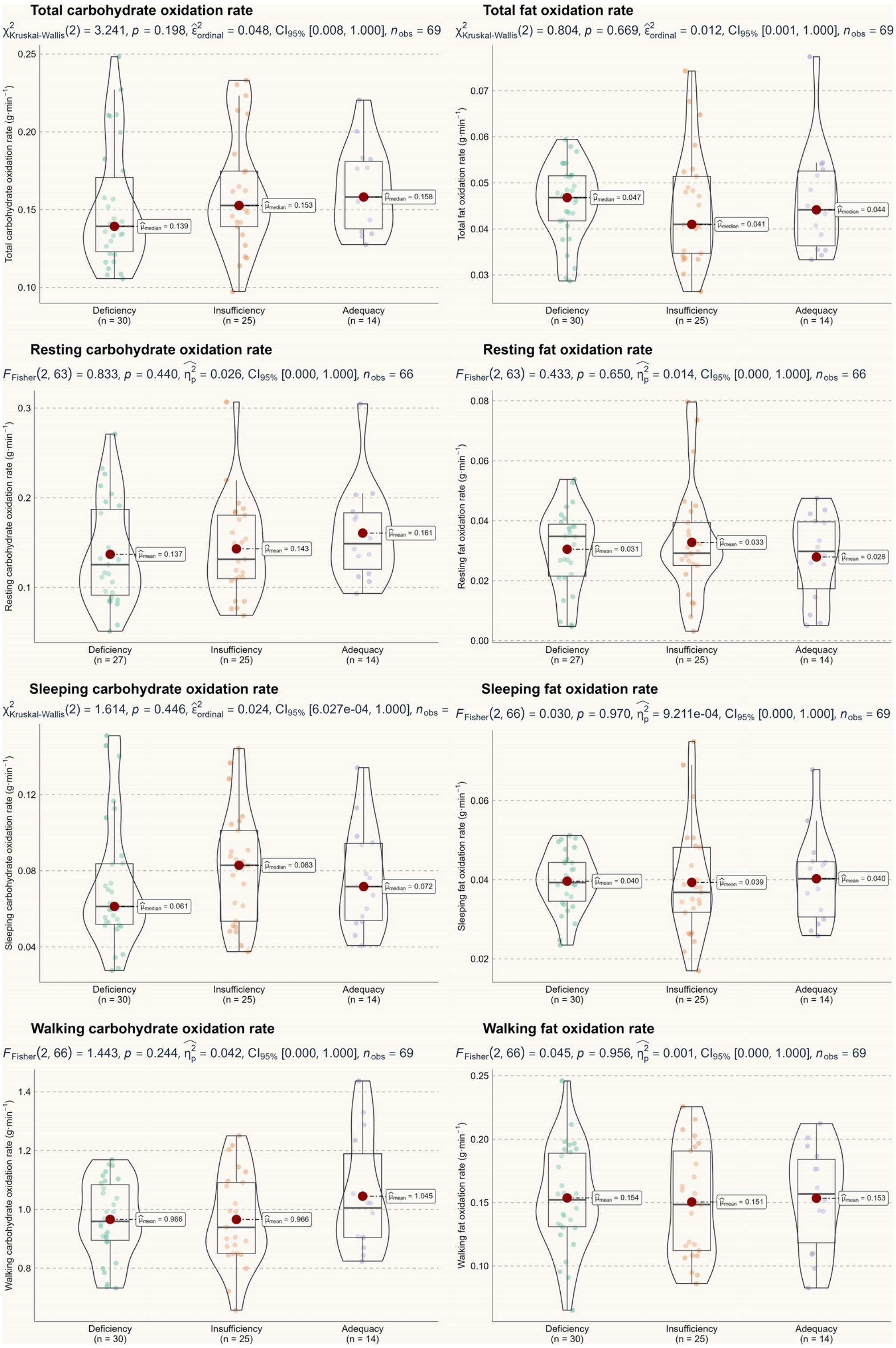


FIGURE 3
Substrate oxidation rate by serum 25(OH)D status.

Table 4 summarizes the correlations between 25(OH)D status and the lipid profile. Although statistically significant relationships were observed for total cholesterol, high-density lipoprotein, and free fatty acid, these correlations were weak.

# 4 Discussion

In a group of young, healthy, non-obese adults, we demonstrate that total 25(OH)D status does not influence energy expenditure or

TABLE 3 Results of seasonality effect.

| Variable | ANOVA | Spring | Summer | Autumn |
|---|---|---|---|---|
| TEE (KJ) | $F_{Welch}(2, 40.5) = 31.9$, $p < 0.001$ | 7184 ± 1002 | 5629 ± 666*** | 5436 ± 317### |
| REE (KJ) | $F_{Welch}(2, 42.5) = 33.1$, $p < 0.001$ | 6454 ± 1229 | 4415 ± 736*** | 4175 ± 553### |
| SEE (KJ) | $F_{Welch}(2, 39.4) = 41.2$, $p < 0.001$ | 1663 ± 272 | 1136 ± 153*** | 1140 ± 69### |
| WEE (KJ) | $F_{Fisher}$ $(2, 66) = 4.6$, $p = 0.014$ | 671 ± 91 | 614 ± 77* | 608 ± 63# |
| TCOR (g·min$^{-1}$) | $F_{Welch}(2, 42.7) = 35.6$, $p < 0.001$ | 0.194 ± 0.031 | 0.143 ± 0.021*** | 0.130 ± 0.017### |
| TFOR (g·min$^{-1}$) | $F_{Fisher}$ $(2, 66) = 4.6$, $p = 0.03$ | 0.050 ± 0.013 | 0.042 ± 0.009* | 0.044 ± 0.007 |
| RCOR (g·min$^{-1}$) | $F_{Fisher}$ $(2, 63) = 24.7$, $p < 0.001$ | 0.194 ± 0.056 | 0.122 ± 0.033*** | 0.111 ± 0.033### |
| RFOR (g·min$^{-1}$) | $F_{Welch}(2, 40.1) = 1.0$, $p = 0.4$ | 0.035 ± 0.022 | 0.028 ± 0.012 | 0.030 ± 0.010 |
| SCOR (g·min$^{-1}$) | $F_{Fisher}$ $(2, 66) = 33.3$, $p < 0.001$ | 0.106 ± 0.028 | 0.060 ± 0.018*** | 0.061 ± 0.018### |
| SFOR (g·min$^{-1}$) | $F_{Fisher}(2, 66) = 5.8$, $p = 0.005$ | 0.045 ± 0.013 | 0.036 ± 0.010** | 0.037 ± 0.007# |
| WCOR (g·min$^{-1}$) | $F_{Fisher}(2, 66) = 5.2$, $p = 0.008$ | 1.050 ± 0.171 | 0.974 ± 0.133 | 0.906 ± 0.133## |
| WFOR (g·min$^{-1}$) | $F_{Fisher}(2, 66) = 1.8$, $p = 0.2$ | 0.161 ± 0.041 | 0.141 ± 0.039 | 0.157 ± 0.041 |

Data are expressed as mean ± standard deviation. TEE, total energy expenditure; REE, resting energy expenditure; SEE, sleeping energy expenditure; WEE, walking energy expenditure; TCOR, total carbohydrate oxidation rate; TFOR, total fat oxidation rate; RCOR, resting carbohydrate oxidation rate; RFOR, resting fat oxidation rate; SCOR, sleeping carbohydrate oxidation rate; SFOR, sleeping fat oxidation rate; WCOR, walking carbohydrate oxidation rate; WFOR, walking fat oxidation rate. *$p < 0.05$ for spring vs. summer; #$p < 0.05$ for spring vs. autumn; **$p < 0.01$ for spring vs. summer; ##$p < 0.01$ for spring vs. autumn; ***$p < 0.001$ for spring vs. summer; ###$p < 0.001$ for spring vs. autumn. Excluding the estimated RCOR and RFOR, the sample sizes for spring, summer, and autumn were 24, 26, and 19, respectively. For the estimated RCOR and RFOR, we lost measurements from one participant in each.

lipid profiles typically associated with overweight and obesity. A novel aspect of this study is that the findings are based on 24-hour continuous measurements of typical human activities conducted in a metabolic chamber. The comprehensiveness of this data set provides new insights into the role of vitamin D in human energy metabolism.

In rodent models, vitamin D receptor-null or vitamin D-deficient mice exhibit an enhanced rate of fatty acid β-oxidation in white adipose tissue and reduced lipid accumulation in the liver, both of which are beneficial for weight management (18, 19). However, it is now clear that these results are not transferable to humans. A substantial body of literature demonstrates an inverse relationship between circulating 25(OH)D levels and fat mass in children (20), adults (21), and even athletes (22). Emerging cellular evidence suggests a potential causal relationship (23), leading to new hypotheses that propose vitamin D status could serve as an adjuvant therapy for unfavorable metabolic phenotypes (24, 25). This existing research prompted the present study, which aimed to clarify the relationship between vitamin D status and human energy metabolism. However, none of the key metrics — energy expenditure or substrate oxidation — differed among non-obese adults with deficient, insufficient, or sufficient 25(OH)D status. Similarly, the significant yet weak correlations between 25(OH)D status and lipid profile do not provide conclusive evidence regarding vitamin D's role in body weight regulation. To our knowledge, this is the first study to report negative evidence under controlled metabolic chamber conditions.

TABLE 4 Correlations between the log transformed serum 25(OH)D (explanatory variable) and lipid profile (response variable).

| Response variable | Statistics |
|---|---|
| ln(Total cholesterol) | $t(67) = -2.33$, $p = 0.02$, $r = -0.27$, $CI_{95\%} = -0.48$ to -0.04 |
| ln(Low-density lipoprotein) | $S = 62311$, $p = 0.26$, $\rho = -0.14$, $CI_{95\%} = -0.37$ to 0.11 |
| ln(High-density lipoprotein) | $t(67) = -2.50$, $p = 0.02$, $r = -0.29$, $CI_{95\%} = -0.49$ to -0.06 |
| ln(Triglycerides) | $S = 62655$, $p = 0.24$, $\rho = -0.14$, $CI_{95\%} = -0.37$ to 0.10 |
| ln(Free fatty acid) | $t(65) = -2.34$, $p = 0.02$, $r = -0.28$, $CI_{95\%} = -0.49$ to -0.04 |

Despite the well-established inverse association between 25(OH)D status and obesity, our findings suggest that low vitamin D status may not be the cause of unfavorable metabolic phenotypes but rather a consequence. This helps explain the conflicting results between observational and intervention studies (9). Several plausible explanations support this notion. First, aside from dietary sources and supplementation, sun exposure is the main contributor to endogenous cholecalciferol production in the skin. Overweight and obese individuals, often due to low mobility and motivation, engage in less outdoor physical activity (26, 27), which limits natural vitamin D synthesis. Second, overweight and obesity disrupt adipose tissue homeostasis and induce hepatic dysfunction, both of which can affect vitamin D metabolism. In obese individuals, the expression of the cytochrome P450 gene family — the primary 25(OH)D hydroxylase — is down-regulated (28, 29), interfering with downstream circulating 25(OH)D activity. Evidence from obese patients undergoing gastric bypass surgery demonstrates that obesity impacts vitamin D metabolizing enzyme expression in the liver, indicating that being overweight leads to lower 25(OH)D status rather than the reverse (30). Relatedly, since vitamin D is fat-soluble and stored in adipose tissue, individuals with higher adiposity tend to have lower circulating 25(OH)D levels (31) and exhibit a blunted response to vitamin D supplementation (32). Our findings align with the theory that low 25(OH)D status is a result of unfavorable metabolic phenotypes (33), suggesting that non-obese, metabolically active young individuals are unlikely to develop overweight solely due to vitamin D deficiency. Given the potential adverse effects of large doses of vitamin D supplementation (34), healthy young individuals are not advised to take additional vitamin D solely for weight management purposes.

Of note, only 20% of participants met the Chinese standard for vitamin D sufficiency. This poor vitamin D status is consistent with epidemiological studies from other regions in China (35, 36). Vitamin D status is linked to a wide range of health benefits, including immunity (37), epigenetics, and gene regulation, particularly in the context of healthy aging (38). Our participants may lack not only professional knowledge about the benefits of vitamin D but also the resources to regularly check their vitamin D status. From a population management perspective, we recommend that the government include vitamin D status assessments in residents' optional annual medical check-ups. Furthermore, we suggest that school-aged adolescents be required to complete a mandatory health course covering nutrition, health behavior, and other essential life skills.

Additionally, it is important to note that while seasonality does not affect the main conclusions of the study, participants enrolled during the spring season exhibited significantly higher energy expenditure and substrate oxidation rates. Although all participants were recruited from the Shanghai University of Sport, they are not all alike. For example, ball sports athletes may have elevated daily energy metabolism. As a result, certain group of participants who took part in the experiment during spring may have higher basal metabolic rate. This seasonal effect could create a misleading impression that the general population's energy metabolism is higher in the spring.

Several limitations apply to our study. First and foremost, the results should be interpreted with caution due to the current analytical approach to measuring 25(OH)D. Similar to steroid hormones (39), 25 (OH)D is transported in the blood by vitamin D binding protein and albumin, with only a small fraction of free 25(OH)D entering most cells and exerting physiological functions (40). Therefore, measuring only total 25(OH)D may not accurately reflect an individual's true vitamin D status, particularly in those with higher body mass index (41). As such, free 25(OH)D may provide a more accurate assessment of vitamin D status than total 25(OH)D (42). Future studies should consider including free 25(OH)D as a complementary measure for a more comprehensive evaluation of vitamin D status. In addition, this study recruited participants from a sport-specialized university. From a practical standpoint, this population may be more metabolically active, potentially diminishing any small effects of vitamin D status on energy metabolism. Conversely, typical Chinese youth tend to be less physically active (43). Furthermore, there was considerable individual variation in the main results (see Figures 2 and 3), indicating significant heterogeneity in metabolic profiles. Therefore, caution is advised when generalizing these findings to the broader population. Finally, vitamin D status may be influenced by genetic variations, such as mutations in the CYP2R1 gene (44). However, this is less well-documented in the Chinese population (45) and warrants further investigation.

In conclusion, there is no relationship between serum 25(OH)D status and energy metabolism among young, healthy, non-obese adults. The current body of evidence indicates that being overweight and obesity are the causes of low vitamin D status, rather than the reverse. While further research may be needed to strengthen the overall evidence, we recommend that future studies prioritize intervention approaches, such as exercise, to improve metabolic health and explore their secondary effects on vitamin D status.

## Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: DOI: 10.6084/m9.figshare.27280311.v1.

## Ethics statement

The studies involving humans were approved by Ethics Committee of the Shanghai University of Sport. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

## Author contributions

LZ: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. HC: Writing – original draft, Software, Methodology, Investigation. XB: Writing – review & editing, Supervision, Project administration, Funding acquisition, Formal analysis. WX: Writing – review & editing, Software, Methodology, Investigation, Data curation, Conceptualization. Z-BC: Writing – review & editing, Resources, Investigation, Formal analysis, Conceptualization. YZ: Writing – review & editing, Validation, Supervision, Methodology.

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## Conflict of interest

The 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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# Evaluating handgrip strength and functional tests as indicators of gait speed in older females

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**Introduction:** With aging, females often experience greater declines in functional capacity [e.g., gait speed (GS)] compared to males, highlighting the need for sex-difference considered in screening and intervention planning. In certain contexts, assessing GS may not be feasible. Handgrip strength (HGS) commonly used as a surrogate measure for physical performance, also serves as an indirect indicator of muscle strength in the lower limbs. This cross-sectional study aims to investigate the associations between HGS and common functional tests and to determine the optimal cut-off values for these tests in assessing GS.
**Methods:** 142 community-dwelling older females aged 60–80 years old (mean age: 75 ± 6 years) were evaluated with HGS, the 30-second arm curl (30 s-AC), 30-second chair stand (30 s-CS), the Short Physical Performance Battery (SPPB), and the 8-foot Up & Go (8-UG) test. Pearson's correlation (r) was used to assess the strength of associations between HGS and functional variables, while multiple linear regression models identified determinants of GS. Receiver operating characteristic (ROC) curves were employed to evaluate the effectiveness of various tests in detecting slow GS (<1.0 m/s), by means of the area under the curve (AUC), sensitivity, and specificity.
**Results:** HGS showed positive significant ($p < 0.001$) associations with 30 s-AC (r = 0.499), SPPB (r = 0.447), and 30 s-CS (r = 0.329). Standardised coefficients of the linear models were: 30 s-AC ($\beta$=0.593), 30 s-CS ($\beta$=0.513), 5-CS ($\beta$=−0.431), and HGS ($\beta$=0.475) (all $p < 0.001$). ROC analysis revealed the following results: 30 s-AC (AUC = 0.80, cut-off=~16 repetitions, sensitivity 83%, specificity 36%), 30 s-CS (AUC = 0.74; cut-off=~13 repetitions, sensitivity 78%, specificity 64%), and 5-CS (AUC = 0.75, cut-off = 10.0 s, sensitivity 81%, specificity 57%), HGS (AUC = 0.73, cut-off=~20 kg, sensitivity 79%, specificity 46%).
**Discussion:** We found that HGS was moderately-to-weakly associated with functional outcomes in older females, indicating that it may not reflect the overall body functional capacity. Despite similar AUCs across all tests, the 30 s-CS and 5-CS showed a better balance of sensitivity and specificity, making them potential indicators of slow GS compared to HGS and 30 s-AC.

KEYWORDS
older women, physical function, mobility limitation, gait speed, grip strength, cross sectional study

# 1 Introduction

The aging process involves complex physiological, metabolic, structural, and functional changes that result in a progressive reduction of mobility, independence, and overall quality of life (1, 2). A significant contributor to this decline is the loss of muscle mass, which diminishes muscle strength and power, impairing the ability to perform daily activities such as walking and climbing stairs (3, 4). These changes are associated with an increased risk of falls, frailty, and reduced life expectancy, particularly in older adults who experience more pronounced functional impairments.

Sex differences play a crucial role in how these age-related declines manifest. In females, these declines are exacerbated by a significant reduction in sex hormone concentrations following menopause, coupled with an increased risk of osteoarthritis and reduced baseline muscle strength (5). Consequently, females experience a slightly greater decline in performance compared to males, particularly after the age of 60. Among the measurable indicators of functional decline, gait speed is particularly valuable. Gait speed is strongly associated not only with life expectancy and adverse health outcomes but also with other measures such as handgrip strength (HGS), lower limb strength, and balance assessments (6–8). Research indicates that females walk slower than males by approximately 0.054 m/s on average. While this difference may seem small, it has practical implications, as slower gait speed is associated with reduced functional capacity, increased risk of falls, and greater dependence on daily activities, especially among older adults (9). This highlights the need to account for sex-specific differences when assessing mobility and planning interventions. However, direct assessments of gait speed may not always be feasible, especially in contexts with space or cognitive constraints (10).

In such cases, alternative, easy-to-administer measures that approximate gait speed are needed. HGS has emerged as a practical proxy for muscle strength and functional abilities, given its simplicity and accessibility (6, 7, 11). HGS is commonly used to estimate lower limb strength and overall physical performance, including mobility. However, while muscle weakness is a primary contributor to slow gait speed in older populations (12, 13), other factors such as balance impairments, neurological conditions, and reduced coordination also influence mobility (14). The relationship between HGS and gait speed is not fully understood, particularly when considering sex-related differences. This raises the need to further evaluate whether HGS can effectively classify individuals with slow gait speed, especially in female populations.

Functional tests such as the chair stand [in five-repetition (5-CS) or in thirty-second (30 s-CS)] are also employed to evaluate functional status in older adults (7). Compared to HGS, the chair stand test can assess a broader range of factors, including sensorimotor integration, psychological readiness, and balance (15). However, often the chair stand might be perceived as more challenging than the HGS, with the consequence that older individuals might not be able to complete the test appropriately (15). This occurrence appears to be particularly relevant in the female population. In fact, females generally take longer than males to complete the chair stand test, and this is likely due to inferior lower extremity muscle strength and a higher prevalence of osteoarthritis (16).

In light of the aforementioned considerations, it becomes crucial to establish specific cut-off values for different functional tests to classify individuals with low gait speed. Although several studies have focused on determining accuracy and cut-offs for HGS (10, 17), and a few have examined the 5-CS (8, 16), there is a lack of comprehensive research comparing multiple functional assessments [i.e., HGS, 5-CS, 30 s-CS and thirty-second arm curl (30 s-AC)] to discriminate their effectiveness in predicting low gait speed in specific populations.

This study aims to fill this gap by focusing on community-dwelling older females. Given the widespread use of HGS in clinical settings, the first goal of the study was to investigate the associations between HGS and other measures of upper and lower limbs strength (e.g., 30 s-AC, 5-CS, 30 s-CS) and overall physical performance (Short Physical Performance Battery ((SPPB), which includes the gait speed test) and 8-foot Up & Go (8-UG)). We hypothesized that HGS would demonstrate weaker associations with lower body strength (e.g., 5-CS, 30 s-CS) and performance (gait speed).

A second goal of the study was to establish optimal cut-off values for the most common functional tests (i.e., HGS, 5-CS, 30 s-CS and 30 s-AC) in the classification of individuals with low vs. adequate gait speed. We hypothesized that functional tests incorporating lower extremity strength (e.g., 5-CS and 30 s-CS) would offer better sensitivity and specificity in identifying individuals with slow gait speed compared to HGS or 30 s-AC, reflecting the greater relevance of these measures to walking ability.

# 2 Materials and methods

## 2.1 Study design and participants

This cross-sectional study was carried out in the Northwest of Italy, and all procedures were conducted in accordance with the Declaration of Helsinki. The study protocol received approval from the Ethical Committee of the University of Verona (registration number #04/2024).

Participants were recruited through a combination of community outreach efforts, including flyers posted at local senior centres, University, health clinics, and community events, as well as word-of-mouth referrals. Eligible participants were community-dwelling older females aged 60–80 years who lived independently and were confirmed to be free from severe physical and cognitive impairments or arthritis through self-report and screening assessments conducted during recruitment. To ensure the reliability of the results, females who were unable to adhere to the testing sessions due to cognitive or physical limitations were excluded. Participants were interviewed before the testing sessions to confirm that they were feeling well and had not taken any substances, such as pain medications or caffeine, that might affect their performance. Those who self-reported feeling unwell or reported the intake of such substances were excluded. Prior to participation, all participants signed written informed.

## 2.2 Anthropometric indices

Body mass and stature were assessed respectively with an electronic scale and a Harpenden Stadiometer to calculate the BMI [as weight (kg)/height $(m)^2$] of each participant (18). All the tests were performed in a single session.

## 2.3 Functional evaluations

The maximal strength of the upper limbs was evaluated with a handgrip dynamometer (Lafayette Instrument, Lafayette, IN, USA). Participants were instructed to stand upright with their arm, forearm, and wrist in a neutral position and apply maximum hand grip pressure for a maximum of five seconds. Three trials using the dominant arm were conducted, each separated by a one-minute rest period (19). The highest peak expressed in absolute units was used for the analysis (19).

The 30 s-AC and 30 s-CS tests were collected to measure participants' muscular endurance strength (20). In the 30 s-AC test, participants performed as many flexion-extension movements of their dominant elbow with a 2.3 kg dumbbell within a 30-s time frame. In the 30 s-CS test, participants performed the maximum number of full stand-ups from a seated position within a 30-s time frame, ensuring proper form with arms crossed on their chest and achieving a full range of motion (i.e., standing fully upright). Any repetitions that did not meet these criteria were not counted. Global physical performance was evaluated using the SPPB test, which consists of a 4-m walk at customary gait speed, a 5-CS, and three standing balance tests (side-by-side, semi-tandem, and tandem) (21). Both the gait speed and 5-CS tests were performed twice, with the best trial recorded, while the three standing balance tests were performed only once, following the standardized guidelines. During each test, the experimenter used a stopwatch to record the time, assigning a score from zero to four points based on recommended cut-off values. The maximum score achievable on the SPPB 12 points, calculated by summing the scores from each category (21). Gait speed, a core outcome of this study, was assessed as part of the SPPB.

Finally, the 8-UG test was administered to assess participants' mobility and functional capacity. The test began with participants seated in the chair (~46 cm seat height), with their back against the chair and arms resting on the armrests (20). Upon hearing the "*go*" signal, participants were instructed to stand up, walk at a comfortable and safe pace to a marked line on the floor 2.8 meters away, turn around, return to the chair, and sit down again. No physical assistance was provided during the test. In the end, the experimenter used a stopwatch to collect the time in seconds to complete the task. Participants completed two trials, and their best performance from the trials was utilized for the analysis.

## 2.4 Statistical analysis

The data were summarized as mean ± standard deviation. Normality was assessed using the Shapiro-Wilk test. To evaluate the association between HGS and functional variables, Pearson's correlation coefficient (r) was used based on the normality assumption. The strength of the associations was categorized as follows: <0.4 indicating a *weak* association, 0.4–0.6 representing a *moderate* association, and >0.6 indicating a *strong* association (22). Additionally, a simple linear regression analysis was conducted to explore which outcome more accurately predicted gait speed (i.e., the dependent variable in each of the models). Seven linear models were created, and the coefficients of the linear relationship were retrieved. The slope of the relationship, when data was normalised by the standard error, returned the $\beta$ coefficient for each model. For the different models, the following independent variables were considered: model (1) Age, model (2) BMI, model (3) 30 s-AC, (4) 30 s-CS, (5) Tandem, (6) 5-CS, (7) HGS. A *p*-value for each linear regression model was reported. Finally, receiver operating characteristic (ROC) curves were generated to evaluate the ability of HGS, 5-CS, 30 s-CS and 30 s-AC tests to discriminate between participants with slow gait speed (<1.0 m/s, positive outcome) and those without (>1.0 m/s, negative outcome) (23). Area under the curve (AUC) values were calculated and interpreted as follows: ≤0.6 (*fail*), 0.6–0.7 (*poor*), 0.7–0.8 (*fair*), 0.8–0.9 (*good*), 0.9–1.0 (*excellent*) (24). Optimal cut-off values were determined based on the point that provided the best balance between sensitivity (i.e., the true positive rate) and specificity (i.e., the true negative rate) for identifying participants with low GS.

Analysis was performed using SPSS statistics software (Version 23.0, Chicago, IL, USA), and the statistical significance was set at $p < 0.05$.

## 2.5 Statistical power calculation

A statistical power calculation was conducted using G*Power 3.1 software. In a study (25) conducted on a cohort of 209 older individuals (mean age 75 years), a positive association between HGS and gait speed was reported in the group of females ($r = 0.30$). Drawing from these findings, we conducted a sample size analysis for Pearson's correlation coefficient in our study, aiming for a statistical power of 0.8 and a significance of 0.05. The analysis revealed that a minimum of 84 participants would be required to detect a significant association between HGS and gait speed. This sample size estimation accounts for a weak effect size within the population.

# 3 Results

The main characteristics of the study participants are presented in Table 1. A total of 142 older females were included in the study, with

16 participants (11%) classified as having obesity (8 with class I and 3 with class II obesity). Additionally, 71 participants (approximately 50%) were classified as having low gait speed (i.e., GS < 1 m/s).

## 3.1 Association analysis between handgrip strength and functional outcomes

The results of the association analyses between HGS and other variables are presented in Table 2. A moderate association was found between HGS and 30 s-AC and SPPB total score while showing a weak association with tandem and 30 s-CS (all $p < 0.001$). No significant associations were observed between HGS and age, BMI, 5-CS, gait speed, and 8-UG ($p > 0.05$).

## 3.2 Linear regression analysis between gait speed and functional outcomes

The results of the linear regression analysis are summarized in Table 3. In model 3, examining the relationship between 30 s-AC and gait speed, the standardized $\beta$ coefficient was 0.593. This suggests that for each standard deviation increase in 30 s-AC (approximately four repetitions), there was a corresponding increase of 0.14 m/s in gait speed. Similarly, in model 4 for the relationship between 30 s-CS and gait speed, the standardized $\beta$ for the 30 s-CS was 0.513, indicating that each one standard deviation increase in the 30 s-CS (approximately four repetitions) was associated with a 0.12 m/s increase in gait speed. In model 5, focusing on the relationship between tandem and gait speed, the standardized $\beta$ for tandem was 0.338, meaning that each standard deviation increase in tandem (approximately 2.4 s) corresponded to a 0.08 m/s increase in gait speed.

Conversely, in model 6 for the relationship between the 5-CS and gait speed, the standardized $\beta$ for 5-CS was −0.431, indicating that each standard deviation increase in 5-CS (approximately 3.6 s) led to a decrease of 0.1 m/s in gait speed. In model 7, examining the relationship between HGS and gait speed, the standardized $\beta$ for HGS was 0.475, indicating that each standard deviation increase in HGS (approximately 5.5 kg) corresponded to a 0.1 m/s increase in gait speed. No significant results were observed in models 1 and 2.

TABLE 1 Characteristics of study participants.

| Variables | *n* = 142 |
|---|---|
| Age (years) | 75.0 ± 6.3 |
| Height (m) | 1.59 ± 0.06 |
| Weight (kg) | 63.8 ± 10.6 |
| BMI (kg/m$^2$) | 25.4 ± 4.0 |
| 30 s-AC (n) | 15.8 ± 3.7 |
| 30 s-CS (n) | 13.1 ± 3.7 |
| SPPB (score) | 10.7 ± 1.6 |
| Semi-tandem (s) | 9.9 ± 0.8 |
| Tandem (s) | 9.2 ± 2.4 |
| 5-CS (s) | 11.9 ± 3.6 |
| GS (m/s) | 1.01 ± 0.23 |
| 8-UG (s) | 7.2 ± 2.2 |
| HGS (kg) | 21.4 ± 5.5 |

Data are presented as mean ± SD.
Abbreviations: BMI, body mass index; 30 s-AC, 30-second arm curl; 30 s-CS, 30-second chair stand; SPPB, short physical performance battery; 5-CS, chair stand in five-repetition; GS, gait speed; 8-UG, foot up and go; HGS, handgrip strength.

TABLE 2 Coefficient correlation between handgrip strength and other variables.

| Variables | r | | *p*-value |
|---|---|---|---|
| Age (years) | −0.423 | weak | 0.343 |
| BMI (kg/m$^2$) | −0.084 | weak | 0.070 |
| 30 s-AC (n) | 0.499 | moderate | <0.001 |
| 30 s-CS (n) | 0.329 | weak | <0.001 |
| SPPB (score) | 0.447 | moderate | <0.001 |
| Tandem (s) | 0.238 | weak | <0.001 |
| 5-CS (s) | −0.396 | weak | 0.082 |
| GS (m/s) | 0.475 | moderate | 0.320 |
| 8-UG (s) | −0.380 | weak | 0.500 |

Abbreviations: BMI, body mass index; 30 s-AC, 30-second arm curl; 30 s-CS, 30-second chair stand; SPPB, short physical performance battery; 5-CS, chair stand in five-repetition; GS, gait speed; 8-UG, foot up and go.

TABLE 3 Linear regression models between gait speed and different functional tests.

| Models | Variables | Standardized coefficient | | *p*-value |
|---|---|---|---|---|
| | | $\beta$ | t | |
| Model 1 ($R^2 = 0.129$) | Constant | −0.359 | 9.296 | <0.001 |
| | Age | | −4.548 | 0.093 |
| Model 2 ($R^2 = 0.023$) | Constant | −0.150 | 9.411 | <0.001 |
| | BMI | | −1.691 | 0.093 |
| Model 3 ($R^2 = 0.352$) | Constant | 0.593 | 6.309 | <0.001 |
| | 30 s-AC | | 8.711 | <0.001 |
| Model 4 ($R^2 = 0.263$) | Constant | 0.513 | 9.744 | <0.001 |
| | 30 s-CS | | 7.064 | <0.001 |
| Model 5 ($R^2 = 0.114$) | Constant | 0.338 | 9.917 | <0.001 |
| | Tandem | | 4.248 | <0.001 |
| Model 6 ($R^2 = 0.186$) | Constant | −0.431 | 9.411 | <0.001 |
| | 5-CS | | −1.691 | <0.001 |
| Model 7 ($R^2 = 0.226$) | Constant | 0.475 | 22.198 | <0.001 |
| | HGS | | −5.651 | <0.001 |

Abbreviations: BMI, body mass index; 30 s-AC, 30-second arm curl; 30 s-CS, 30-second chair stand; 5-CS, chair stand in five-repetition; HGS, handgrip strength.

## 3.3 Determining optimal cut-offs for functional tests: ROC curve analysis

Figure 1 displays the predicted capacity of different functional tests for low gait speed. For the detection of slow gait speed, a 5-CS cut-off value of 10.4 s exhibited a sensitivity of 81% and a specificity of 57%, with an AUC of 0.75 (classified as fair test) [Panel (A)]. This means that using a cut-off of 10.4 s for the 5-CS, we can expect 81% of positive outcomes (indicating slow gait speed) to be correctly classified, while 43% of negative outcomes would be incorrectly identified as positive. Similarly, a HGS cut-off value of 19.95 kg showed a sensitivity of 79% and a

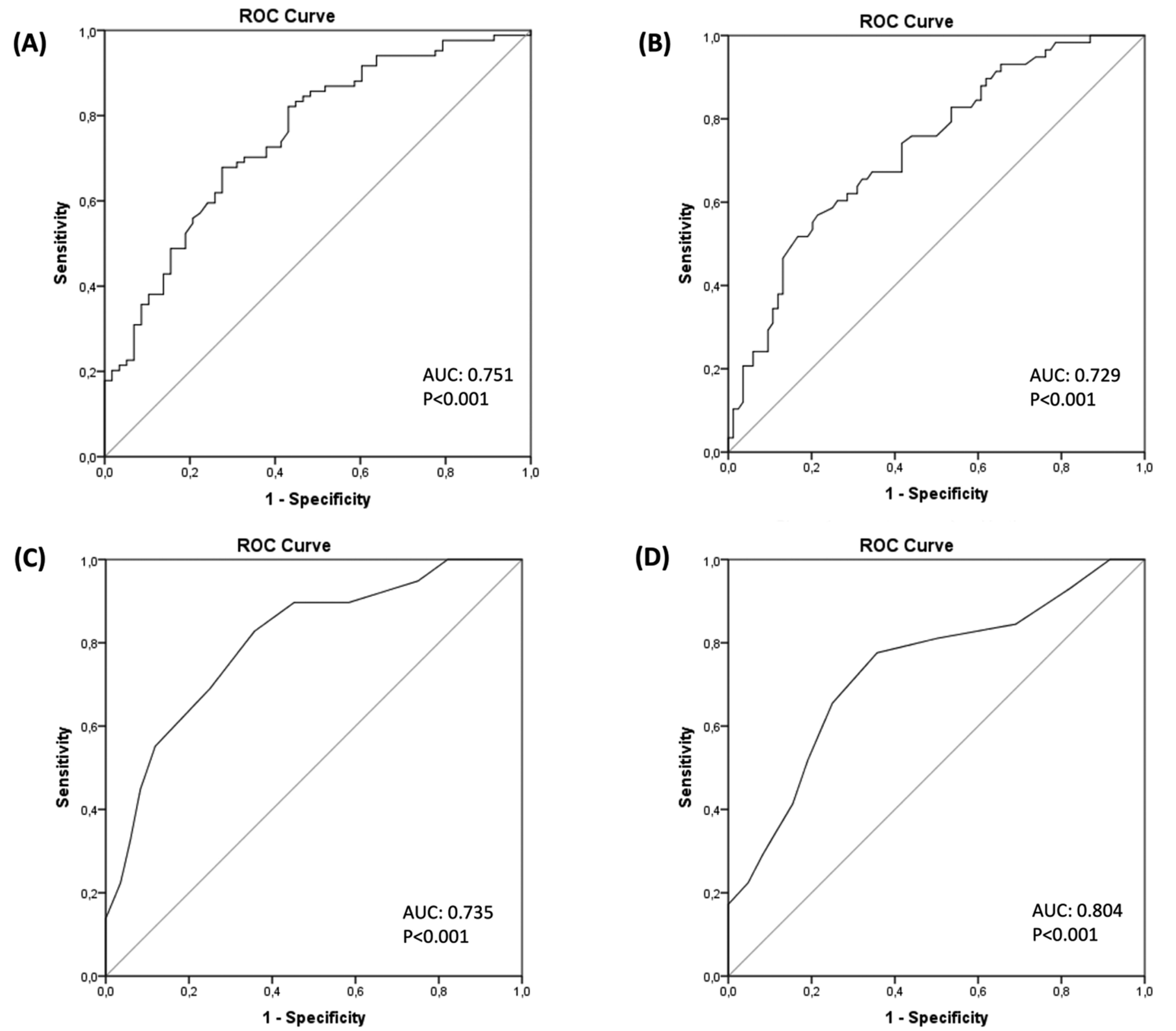


FIGURE 1
Cut-offs identification via ROC curve analysis for functional tests. Receiver operating characteristics curve plots compare how the 5-Chair Stand test [panel **(A)**], Handgrip Strength [Panel **(B)**], 30-second Chair Stand [Panel **(C)**], 30-second Arm Curl [Panel **(D)**] tests allow the identification of older adults with low gait speed. ROC, receiver operating characteristic.

specificity of 46%, with an AUC of 0.73 (also classified as a fair test) [Panel (B)]. This implies that using a cut-off of ∼20 kg for the HGS, we anticipate correctly classifying 79% of positive outcomes (indicating slow gait speed). In contrast, 54% of negative outcomes would be incorrectly identified as positive.

In the case of the 30 s-CS, a cut-off value of 12.5 repetitions had a sensitivity of 78% and a specificity of 64%, yielding an AUC of 0.74 (classified as a fair test) [Panel (C)]. This suggests that with a cut-off of 12.5 repetitions for the 30 s-CS, we anticipate that 78% of positive outcomes (indicating slow gait speed) would be correctly classified as positive, while 36% of negative outcomes would be incorrectly identified as positive. Finally, for a 30 s-AC test with a cut-off value of 15.5 repetitions, a sensitivity of 83% and a specificity of 64% were observed, resulting in an AUC of 0.80 (classified as a good test) [Panel (D)]. This indicates that by using a cut-off of 15.5 repetitions for the 30-AC, 83% of positive outcomes (indicating slow gait speed) would be correctly classified as positive, while 36% of negative outcomes would be incorrectly identified as positive.

# 4 Discussion

This study focused on community-dwelling older females and our primary objective was to investigate the associations between HGS and gait speed, as well as other functional fitness outcomes. For the first time, we conducted a comprehensive comparison of multiple functional tests (HGS, chair stand, and arm curl tests) to assess their relative contributions to functional capacity and gait speed, focusing on a large sample of older females.

Additionally, we aimed to identify key functional factors influencing gait speed and establish optimal cut-off values for these tests, especially for cases where individuals are unable to walk or when the space available to perform the test is limited.

The correlation analyses returned significant associations between HGS and various functional outcomes. Notably, HGS showed moderate associations with 30 s-AC and SPPB total score. However, weak associations were observed with tandem and 30 s-CS, while no significant associations were found with the 8-UG and 5-CS. As expected, these findings suggest that HGS may not always fully capture lower body function. While HGS is a useful indicator of overall muscle strength, it primarily reflects upper body strength and may not directly capture the more specific lower body functional impairments that influence gait performance. Key functional factors directly affecting gait performance include lower limb strength, balance, and coordination (14). Among the measures used in this study, tests like the 5-CS and 30 s-CS tests are more directly linked to gait performance, as they assess lower extremity strength, dynamic balance, and coordination, all of which are critical components for effective walking (26). These tests are more directly related to the muscles and systems responsible for gait, whereas HGS, though important, may not provide a complete picture of the functional limitations impacting walking speed.

A recent review (27) presented conflicting results concerning the relationship between HGS and overall physical performance, particularly in terms of lower muscle strength. The limited number of studies explicitly focused on older females, coupled with the different tests used, makes direct comparisons challenging. For instance, Wisnowska et al. (25) identified weak associations between HGS with age ($r = -0.18$, $p = 0.053$), chair stand performance in seconds ($r = -0.27$), and 10-m gait speed ($r = 0.30$), with no significant associations observed with BMI. While the findings for age and HGS did not reach statistical significance (trend with $p = 0.053$), they suggest a potential relationship that warrants further exploration. Similarly, in our study, we observed weak but nonsignificant associations between HGS and age and BMI, alongside a significant association with 30 s-CS performance. Together, these findings underscore the variability in how HGS relates to different functional outcomes, which may be influenced by population characteristics or test-specific factors. Similarly, another study (28) involving older adults of both sexes, found weak or no associations between HGS and the timed up-and-go test under different conditions (acoustic evaluation, pre-recorded sound signal, and visual assessment). Our findings corroborate some of these results, underscoring the importance of exercising caution when using HGS alone as a surrogate for more complicated measures of arm and leg strength (7) or performance (27). Tasks like rising from a chair involve muscles beyond those involved in gripping, contributing to the observed weak association between HGS and lower limb performance (29). Consequently, the absence of robust associations between HGS and lower limb performance should not be surprising (29), and further supports the need to perform multiple tests to achieve more accurate assessments in older females.

Simple linear regressions were chosen to clearly illustrate the direct impact of each functional test on gait speed. This approach allowed us to isolate the influence of each variable without the complications of multicollinearity that may arise in multiple regression models. Although future studies could use multiple regression to explore these relationships in greater depth, we opted for simpler models to avoid increasing the $R^2$ value unnecessarily by including variables of unknown importance. The analyses revealed a significant relationship between functional outcomes and gait speed, with increases in both 30 s-AC and 30 s-CS tests being strongly associated with corresponding improvements in gait speed. Specifically, we observed that an increase of approximately four repetitions in the 30 s-AC and 30 s-CS tests was associated with a gait speed increase of 0.14 m/s and 0.12 m/s, respectively. Similarly, improvements in HGS by around 5.5 kg and a reduction in the 5-CS test time by 3.6 s were associated with a gait speed increase of 0.1 m/s each. To put these results in perspective, a change in gait speed between 0.05–0.1 m/s is considered clinically meaningful (6), while the clinically meaningful change for the 5-CS and HGS are 2.3 s (6) and 5.0–6.5 kg, respectively (30). Our study contributes to the growing body of literature by confirming these associations and providing specific quantitative relationships that can inform clinical assessments and interventions.

The prevalence of slow gait speed is highly dependent on the cut-off values adopted, such as 0.8 m/s vs. 1.0 m/s (31). Setting the cut-off value to 0.8 m/s may lead to an underestimation of individuals with low gait speed who are at increased risk of adverse health outcomes, including enduring lower extremity limitations, hospital admissions, and mortality (32, 33). In this study, we used ROC curve analysis to compare the predictive capacity of different functional tests in detecting slow gait speed. In ROC analysis, a key consideration is whether to prioritize sensitivity or specificity. Sensitivity is prioritized when the goal is to correctly identify individuals at risk (minimizing false negatives), whereas specificity is favoured when avoiding false positives is critical. Given the limited literature on sensitivity and specificity cut-offs for HGS and other functional tests in older populations, calculating an exact sample size for ROC analysis was challenging. Future studies should consider these trade-offs in their design to maximize the clinical relevance of the functional measures being evaluated. Previous studies (10, 17) investigating the link between HGS and gait speed in older females reveal variations in cut-off values for impaired walking speed. Delinocente et al. (17) established a cut-off value of ~21 kg for HGS with 58.6% sensitivity and 72.9% specificity, while Felix et al. (10) found a similar cut-off value with higher sensitivity (100%) and specificity (91%). However, in our cohort, we observed a slightly lower cut-off value of ~20 kg for HGS, resulting in 79% sensitivity, 54% specificity, and an AUC of 0.73. These discrepancies in the cut-off values between studies indicate potential variability in the HGS-walking speed association among older females, influenced by factors like age and sample size. Another study (16) investigated the relationship between walking speed and the 5-CS test in older females. Using a walking speed cut-off value of 0.1 m/s, they determined a 5-CS cut-off of 11.04 s with 68% sensitivity, 67% specificity, and an AUC of 0.74. In our cohort, we identified a similar 5-CS cut-off of 10.4 s, with 81% sensitivity, 57% specificity, and an AUC of 0.75. These findings suggest the potential utility of the 5-CS test in assessing functional performance, particularly regarding gait speed in older females. However, differences in sensitivity and specificity between the studies highlight the potential variations across populations of older females. Furthermore, discrepancies in the results between the two chair stand tests may be attributed to several factors. Although both tests exhibit a strong association, they likely assess different aspects of functional performance. The 5-CS test emphasizes dynamic balance and lower-limb strength, while the 30 s-CS test places greater demand on cardiovascular endurance due to its focus on sustaining repetitions over a timed 30-s period.

To our knowledge, previous studies have not extensively explored alternative functional tests such as the 30 s-AC and 30 s-CS for assessing slow gait speed. However, given the limited research on this type of analysis, we chose to dedicate a section to these findings. Our findings suggest that the 30 s-AC could be a valuable tool for identifying individuals with low gait speed (i.e., good sensitivity). In our sample, a cut-off value of 15.6 repetitions suggested low gait speed. While making direct comparisons with other studies is challenging, a previous investigation (34) found that achieving 11 repetitions in the 30 s-AC test was associated with a high risk of loss of functional independence among older adults of both sexes. It is important to note that our study focused on an older female population, with a slightly higher mean age ($75 \pm 6$ years) compared to the referenced research ($72 \pm 8$ years) (34). Despite this age difference, our participants showed a higher mean value (29.5%) on the arm curl test.

Overall, our findings showed varying sensitivities and specificities across different cut-off values, although the AUCs of the tests were similar. Among the functional tests, the 30 s-AC resulted in the highest AUC (0.80) and sensitivity (83%), but the lowest specificity (36%). This highlights the importance of prioritizing what is most crucial—whether it is more important to correctly identify individuals with slow gait speed (sensitivity) or to accurately classify those with normal gait speed (specificity). It is also crucial to assess the cost of misclassification and consider the potential consequences of incorrectly identifying individuals with good mobility as having low gait speed, or vice versa. This decision should be guided by the clinical context and screening objectives. Based on our results, the 30 s-CS, followed by the 5-CS, offered a good balance, with similar sensitivity but much higher specificity (ranging from 7% to 20%) compared to HGS and 30 s-AC.

We acknowledge that this study has some limitations in this study. First, as the data were collected outside the laboratory, we were unable to gather other relevant information on potential confounding factors, including muscle mass, lifestyle factors (e.g., physical activity levels or nutritional status), and anthropometric measurements (e.g., waist or hip circumference) or body composition indices. Notably, the lack of body composition measurements, such as fat distribution, appendicular lean mass, and lower extremity muscle mass, is a limitation. These parameters could have provided more comprehensive insights into the functional outcomes evaluated in this study. Additionally, while participants were interviewed to ensure they felt well and were fit for testing, no formal assessments for infections or fatigue on the testing day were conducted. Similarly, the intake of medications, drugs, or caffeine, which could potentially affect physical performance, was based on self-reports and not systematically documented. Furthermore, metabolic syndrome or obesity, which could have influenced the results, was not formally assessed. Second, our sample only included independent females, limiting the generalizability of our findings to the broader population or individuals with severe health conditions (e.g., a large sample of obese adults or those over 80 years old). Additionally, the absence of a male sample precludes us from drawing conclusions based on sex differences. Another notable limitation is related to the cut-off value for the gait speed used in our study. We were unable to test other commonly used thresholds, such as 0.8 m/s, due to our sample's limited number of participants with gait speeds below this threshold. It is important to note that our sample included females aged 60 and older, with the majority being in their early 70 s. Consequently, we described our sample as consisting of "youngest-older adults," for whom a cut-off of <1 m/s is recommended (8). Hence, while this threshold provides a useful general guideline, its accuracy and applicability could vary and warrant further investigation in future studies.

In conclusion, our study found that HGS showed only a moderate-to-weak association with various functional outcomes in older females, suggesting that HGS alone may not always reflect lower body function. More importantly, we identified the 30 s-CS and 5-CS as potentially offering a good balance between sensitivity and specificity for detecting slow gait speed, which could have clinical implications for screening older adults at risk for mobility limitations. Our study provides specific cut-off values and quantitative associations that can guide clinical assessments and interventions in this population. These findings emphasize the importance of selecting functional tests based on the balance between sensitivity and specificity and tailoring specific clinical test choices to align with specific clinical objectives.

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Ethics statement

The studies involving humans were approved by Ethical Committee of the University of Verona (Italy) (registration number 04/2024). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

## Author contributions

VM: Conceptualization, Formal Analysis, Methodology, Validation, Writing – original draft. SD: Conceptualization, Formal Analysis, Investigation, Methodology, Writing – review & editing. LG: Investigation, Methodology, Writing – review & editing. DR: Investigation, Methodology, Writing – review & editing. FS: Investigation, Project administration, Writing – review & editing. CT: Investigation, Project administration, Writing – review & editing.

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## Conflict of interest

The 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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# Influence of systematic standard and Nordic walking training on exercise tolerance and body weight components in women over 55 years of age

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**Background:** The most physiological form of movement of human body is walking. The aim of the study was to assess the changes before and after workout programme in body mass components and exercise tolerance in women above 55 years of age, both in standard walking (March training) and walking with poles (Nordic Walking).
**Material and methods:** 77 (55–64 years) women were divided into two groups: I - 37 women, participating in the marching training. II - 40 women participating in the Nordic Walking training. CPET, and body composition analysis were performed in each of the participants before and after workout program.
**Results:** Significant changes in VO2peak, both in standard walking group and Nordic walking, distance and test duration were observed. The evaluation of body composition Standard and Nordic Walking groups concerned statistically significant changes in the same indicators at the same level of significance: fat content (%), water content inside and outside the cell (%). In Nordic walking group there where some significant correlations between the changes in body fat (%), body weight, visceral obesity and fitness scores, changes in metabolic cost associated with the exercise test, changes in body fat (%) content and increase in the duration of the exercise test, as well as changes in body fat (%) content and increase in the distance of the test.

KEYWORDS
March, Nordic walking, body mass composition, exercise tolerance, physical activity

## Background

Aging is a physiological process that affects the functioning of most organs and systems. The most characteristic features are a decrease in physical and mental performance, unfavorable changes in the cardiovascular system, decreases in muscle and bone mass, and disturbances in balance and motor coordination. This leads to functional problems and a loss of physical independence. Additionally, numerous concomitant chronic diseases overlap to the detriment of the degenerative process in the elderly (1). Achieving a long life in health, fitness and independence, while delaying the involutionary process, should be sought in pro-health and preventive activities, consisting in an appropriate lifestyle. Regular physical activity, especially in contact with nature, plays a huge role in improving the physical condition and, consequently, mental health (2, 3). Exercise carried out in a natural environment, in the open air or in urban green spaces is better than exercise in closed rooms (4). The most physiological form of movement of human body is walking. A modification of this form of activity is Nordic walking (NW). Using poles during walking engage the muscles of the upper body, which are passive during normal walking. Normal walking and NW are recommended in all age groups (especially the elderly), including people with low physical capacity, overweight or obese people, those with diabetes, chronic obstructive pulmonary disease, Parkinson's disease, or peripheral vascular diseases, pregnant women, and patients at risk (e.g., after a heart attack) in the convalescence phase (5–9).

NW requires a higher expenditure of energy at a given speed compared to normal walking. Nordic walking ensures balance and correct posture, prevents stumbling and falls as well as improves functional fitness, and lowers blood pressure (10, 11). Even if this kind of training is quite popular this days, the number of reports with recommendations related to it for women during or after the menopause (>55 years of age) is small. Most of them are general in nature, without detailed clinical analyses (11, 12). Monitoring of body composition is of significant importance in the assessment of health status, the level of functional capacity, and the course of the aging process (13).

Adverse changes in one or more of its elements increase the risk of age-related diseases (14). Thus, monitoring of body composition has become crucial in assessing the nutritional status of the elderly and middle-aged. One of the most popular methods of assessing body composition is bioelectric impedance analysis (BIA) due to its combination of cost effectiveness, ease of use and portability (15). The accuracy of such a study is quite high, in the range of 3.5%–5% (16). It is difficult to state conclusively which of this two mentioned forms of walking would be the most beneficial in terms of changes in body weight composition, exercise tolerance, and lipid profile for women who enter the period of slow aging after menopause.

Therefore, the aim of the study was to analyze the changes occurring before and after training in the components of body mass and exercise tolerance under in women who systematically use various forms of walking training – ordinary walking training and walking with poles (Nordic walking).

The following research questions were formulated:

1. Which of the two types of systematic and structured walking training (walking without or with poles) leads to greater changes in body weight in mature women (>55 years of age)?
2. Do both forms of training improve exercise tolerance in a similar way?
3. Is there a relationship between the change in the level of exercise tolerance in women (in the analyzed groups) and the change in the composition of their body weight?

# Material and methods

Presented studies are part of research that showed differences between Nordic walking and standard walking at the group of women over 55 years old.

The study was conducted as a randomized controlled longitudinal study with 2 parallel training groups and was considered an exploratory study. The study was approved by the Bioethical Committee (No. 7/2011) and was in line with the standards set out in the Helsinki Declaration.

All patients were informed of the nature and purpose of the study and provided written informed consent prior to enrollment in the study. Participants could withdraw from the study at any time.

## Participants

86 women aged >55 participated in the first stage of the study, taking part in regular recreational activities. The aim of this stage was to eliminate the risk of health or life caused by the presence of disease or insufficient physical capacity. Therefore, each of the examined women was thoroughly diagnosed in a hospital setting (blood laboratory tests, exercise tests on a treadmill, echocardiography of the heart).

Inclusion criteria for the study were: postmenopausal women >55 years old, LVEF ≥50%, normal values of blood pressure or pharmacologically controlled mild hypertension (140–159/90–99 mmHg), stable coronary artery disease. Exclusion criteria: COPD (stage II, III, IV), recent myocardial infarction (<3 months), confirmed symptoms of heart failure, musculoskeletal dysfunction impeding walking, unregulated blood glucose levels, left ventricular ejection fraction <50%, unregulated hypertension grade II or III hypertension, history of acute thrombosis or embolism.

Taking into account the adopted inclusion and exclusion criteria, 77 women were qualified for the second part of the research project. Body weight composition was assessed in each of the women.

Participants were randomly assigned to the CW (conventional) or NW (Nordic walking) group using permuted block randomization [Microsoft Excel 2019 (version 16.0); Microsoft Corp., Redmond, WA]. After starting training programme, several women ($n = 11$) withdrew from the study due to health conditions (infections, $n = 7$) or other reasons (problems participating in the training program, $n = 2$; refusal to continue, $n = 2$). 66 women were included in the final analysis (Figure 1).

## Methods

The tests were carried out on all participants at the beginning (pre-test) and after 12 weeks (*post test*). The spiroergometric submaximal treadmill stress test was performed with a METAMAX 3B CORTEX gas analyzer (CORTEX Biophysik GmbH, Leipzig, Germany) according to Bruce's protocol [seven 3-min levels with increasing speed and incline: starting at 1.7 mph from 10% gradient (upward slope) to a maximum of 5.5 mph with a 20% gradient]. Drugs were not discontinued prior to the study. The following parameters were assessed during the test: resting heart rate (HRrest) and peak heart rate (HR peak)

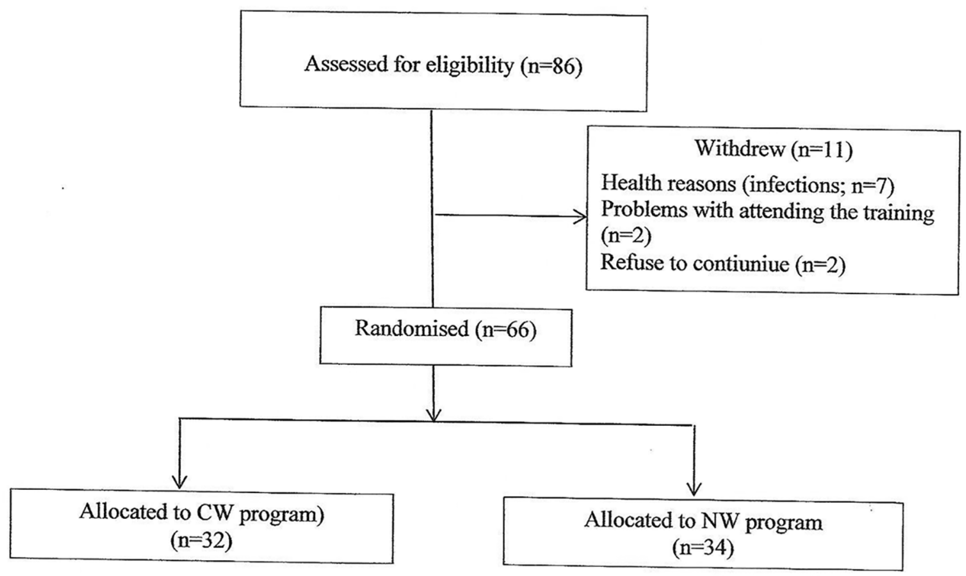


FIGURE 1
Flow diagram.

[bpm], systolic blood pressure at rest (SBPrest) and peak systolic blood pressure (SBPpeak) [mmHg], diastolic blood pressure at rest (DBPrest) and peak diastolic blood pressure (DBPpeak) [mmHg], metabolic equivalents (METs; ml $O_2$/kg/min), peak oxygen consumption [$VO_2$ peak] achieved during the submaximal test [ml/kg/min], distance [m], test duration [min]. Reasons for finishing the test included physiological: submaximal heart rate reached, which was determined by the formula: $(208 - 0.7 \times \text{age}) \times 0.85$ or fatigue and pathological stenocardial pain, deviation in the ST–T segment, arrhythmia and conduction disorders, and increases in blood pressure >250/120 mmHg.

The body mass composition was measured using the InBody 720 device. The following indicators were assessed:

Fitness score – based on the replacement of the muscle and fat fractions in relation to body weight:

≤70 – weak, obese type
70–90 – normal, healthy type
≥90 – athletic type
Visceral fat area (VFA) [$cm^2$]
Body mass [kg]
Skeletal muscle mass (SMM) [kg]
Body fat mass (BFM) [kg]
Percent body fat (PBF) [%]
The risk limits are set at 10%–20% for men, 18%–28% for women
Extracellular water (ECW) [%]
Intracellular water (ICW) [%]
Total body water (TBW) [kg]

Additionally, the level of left ventricular ejection fraction (LVEF) was assessed using echocardiography (ultrasound ALT HDI 3000; Philips, Best, Netherlands). The tests were performed by a cardiologist using 1-dimensional M-mode and 2-dimensional projection in accordance with the recommendations of the American Society of Echocardiography.

Conventional walking and NW were performed 3 times a week for 12 weeks (Table 1). Each training session was held outdoors on an unpaved ground. The effort intensity was estimated using Borg scale: (scale 6–20). All participants were familiar with the scale (perceived exertion rating 11–13). The entire training was supervised by the same physiotherapists who were also NW instructors. All women were taught the correct CW and NW techniques during the first training. All participants were asked not to modify their diet and not to undertake additional physical activity during the training programme. All training sessions, both the classic walking training and Nordic walking, were conducted under the same environmental conditions (a forest park in the vicinity of Katowice, on flat terrain without inclines) as well as at the same time of day (between 2:00 PM and 4:00 PM).

## Statistical analysis

Results are expressed as mean and standard deviation (SD) of the parameters. The normality of the distribution was verified with the

TABLE 1 Walking training programs.

| Type of exercises | Frequency | Duration | Intensity |
|---|---|---|---|
| Conventional walking | 3 days/week | 60 min/day (10-min warmup, 40-min main part, and 10-min cooldown) | Moderate 11–13 rating of perceived exertion |
| Nordic walking | | | |

Shapiro test, and homogeneity of variance was verified by the Brown–Forsythe test. Age, body weight were compared with the *t*-test or the Mann–Whitney *U*-test. It was used repeated-measures analysis of variance with 95% confidence intervals to determine the effects of the NW and CW training programs on aerobic capacity, body mass, and BMI with the pre-exercise and post-exercise measurements as factors. The *post hoc* Tukey test was performed when a significant main effect was detected. To avoid the likelihood of type I error, Bonferroni correction was applied. A high value of power analysis (above 0.8) means that the sample size was sufficient. For imputing missing data (results of posttests) of 8 participants who withdrew from the study after starting the intervention, the hot-deck imputation method was applied. The level of significance was set to $P \leq .05$. The statistical analysis was performed using STATISTICA software v.10.

# Results

The results were analyzed with the intention-to-treat method (participants randomly allocated to one of the walking programs were included in the statistical analysis and analyzed according to the CW or NW group allocation (Figure 1). Participants Baseline Characteristics). The mean age of the CW group was 62.81 ± 5.25 years and body weight was 71.70 ± 13.81 kg, whereas the mean age of the NW group was 61.88 ± 4.87 years and body weight was 70.34 ± 11.97 kg. The differences in age and body weight were not statistically significant.

## Analysis of electrocardiographic exercise test results

After the end of the training program, both the walking group and the Nordic walking group showed a significant increase in exercise tolerance, manifested by an increase in peak heart rate, maximum systolic pressure, oxygen uptake, distance, MET energy expenditure, and an increase in the duration of the exercise test. The intergroup analysis concerning comparisons in terms of changes in the values of individual test values (delta) showed significant differences in the duration of the test, the distance covered and the maximum oxygen consumption (Table 2).

## Analysis of changes in BMI

After the end of the training program in both the walking group and the Nordic walking group, the result did not change. The intergroup analysis also showed no significant differences.

## Analysis of changes in body mass composition indices

In both analyzed training groups, significant changes in the percentage of adipose tissue, external and intracellular water were observed. The intergroup analysis of changes in the examined indicators did not show any significant differences (Table 3).

## Correlation of the level of exercise tolerance and body mass components

### CWG – conventional walking group

There were no statistically significant correlations.

### NWG – Nordic walking group

The results of the analysis show a significant positive relationship between the BMI index and the increase in the duration of the exercise test, metabolic cost and maximum oxygen consumption (Table 4).

The results of the analysis show a significant correlation between changes in body fat (%), body fat mass, body weight, visceral obesity and fitness score and changes in the metabolic cost associated with the exercise test, changes body fat (%) and the increase in the duration of the exercise test, as well as changes body fat( %) content and the increase of distance during the test (Tables 5–8).

# Discussion

The study results confirmed the effectiveness of both walking forms. However, more statistically significant differences were observed in the improvement of exercise tolerance, assessed by the exercise test, in the Nordic Walking group. A similar effect was found in the body composition analysis, but it did not reach statistical significance. A detailed description of the results of individual tests is presented below.

## Electrocardiographic exercise test

Assessment of exercise tolerance is an essential element of physical exercise intensity programming (17, 18). Its result is very important in qualifying for various training programs, including rehabilitation. The popularity of Nordic walking increased the interest in this form of activity among physiologists, biomechanics and physiotherapists (19). During exercise, stimulation of the sympathetic nervous system causes an increased oxygen demand of the heart muscle. The increase in heart rate, its contractility and systolic blood pressure make the ECG stress test an accurate diagnostic test.

Own research showed the effectiveness of both forms of training, but with regard to the level of exercise tolerance, assessed with the exercise test on a treadmill, more favorable results were observed in the Nordic walking group. It was probably influenced by the level of training intensity. In the group of women walking with poles, the energy expenditure associated with the form of training used was significantly higher than in the group without poles, because the intensive work of the upper limbs was additionally involved.

TABLE 2 Results of stress tests before (1) and after (2) training completion.

| Variable | CWG | | | NWG | | |
|---|---|---|---|---|---|---|
| | $\bar{x} \pm$ SD | Δ | *p* | $\bar{x} \pm$ SD | Δ | *p* |
| HRrest [beats/min] 1 | 82.43 ± 11.89 | −1.90 | 0.098 | 79.67 ± 10.49 | −0.97 | 0.103 |
| HRrest [beats/min] 2 | 80.53 ± 10.53 | | | 78.70 ± 9.93 | | |
| ΔCWG vs. ΔNWG | 0.533 | | | | | |
| HRpeak [beats/min] 1 | 137.40 ± 17.48 | 5.25 | 0.015 | 137.35 ± 16.17 | 4.64 | 0.009 |
| HRpeak [beats/min] 2 | 142.65 ± 14.66 | | | 142.00 ± 14.12 | | |
| ΔCWG vs. ΔNWG | 0.881 | | | | | |
| SBPrest [mmHg] 1 | 127.03 ± 14.69 | −0.15 | 0.862 | 129.85 ± 19.52 | −0.88 | 0.789 |
| SBPrest [mmHg] 2 | 126.87 ± 10.93 | | | 128.97 ± 13.19 | | |
| ΔCWG vs. ΔNWG | 0.563 | | | | | |
| DBPrest [mmHg] 1 | 77.50 ± 10.93 | −1.71 | 0.359 | 75.29 ± 10.44 | 0.88 | 0.443 |
| DBPrest [mmHg] 2 | 75.78 ± 9.17 | | | 76.17 ± 7.98 | | |
| ΔCWG vs. ΔNWG | 0.879 | | | | | |
| SBPpeak [mmHg] 1 | 183.28 ± 28.16 | 3.90 | 0.032 | 180.00 ± 28.39 | 2.79 | 0.046 |
| SBPpeak [mmHg] 2 | 187.18 ± 24.43 | | | 182.79 ± 22.40 | | |
| ΔCWG vs. ΔNWG | 0.935 | | | | | |
| DBPpeak [mmHg] 1 | 89.37 ± 16.79 | 3.43 | 0.013 | 85.14 ± 13.95 | 1.61 | 0.194 |
| DBPpeak [mmHg] 2 | 92.81 ± 16.94 | | | 86.76 ± 12.42 | | |
| ΔCWG vs. ΔNWG | 0.355 | | | | | |
| MET 1 | 9.05 ± 2.05 | 0.46 | 0.019 | 8.82 ± 2.11 | 0.78 | 0.01 |
| MET 2 | 9.51 ± 2.18 | | | 9.60 ± 2.09 | | |
| ΔCWG vs. ΔNWG | 0.419 | | | | | |
| $VO_{2peak}$ 1 [ml/kg/min] | 27.47 ± 7.09 | 2.33 | 0.002 | 26.61 ± 7.81 | 4.37 | 0.000 |
| $VO_{2peak}$ 2 [ml/kg/min] | 29.80 ± 8.54 | | | 30.98 ± 10.31 | | |
| ΔCWG vs. ΔNWG | 0.035 | | | | | |
| Distance [m] 1 | 256.34 ± 97.91 | 39.34 | 0.000 | 247.83 ± 107.06 | 59.71 | 0.000 |
| Distance [m] 2 | 295.68 ± 113.6 | | | 307.55 ± 128.58 | | |
| ΔCWG vs. ΔNWG | 0.045 | | | | | |
| Duration [min] 1 | 6.75 ± 2.09 | 0.63 | 0.001 | 6.47 ± 2.24 | 1.13 | 0.000 |
| Duration [min] 2 | 7.38 ± 2.06 | | | 7.60 ± 2.32 | | |
| ΔCWG vs. ΔNWG | 0.002 | | | | | |

All data are presented as mean ± standard deviation and the difference (Δ, delta).
CWG, conventional walking group; NWG, Nordic walking group; HRrest, heart rate at rest; SBPrest, systolic blood pressure at rest; DBPrest, diastolic blood pressure at rest; MET, metabolic equivalent; $VO_2$ peak, peak oxygen consumption; HRpeak, peak heart rate; SBPpeak, peak systolic blood pressure; DBPpeak, diastolic blood pressure.

TABLE 3 Comparison of BMI values before (1) and after (2) the end of training.

| Variable | CWG | | | NWG | | |
|---|---|---|---|---|---|---|
| | $\bar{X} \pm$ SD | Δ | *p* | $\bar{X} \pm$ SD | Δ | *p* |
| BMI [kg/m$^2$] 1 | 29.61 ± 3.88 | −0.3 | 0.634 | 27.94 ± 5.00 | −0.06 | 0.696 |
| BMI [kg/m$^2$] 2 | 29.30 ± 3.91 | | | 27.87 ± 5.02 | | |
| ΔCWG vs. ΔNWG | 0.322 | | | | | |

All data are presented as mean ± standard deviation and the difference (Δ, delta).
CWG, conventional walking group; NWG, Nordic walking group; BMI, body mass index.

Physiological changes in the body related to greater physical effort produced an effect similar to that in competitive or recreational sports, but of course at a much lower level. Comparing the results of the preliminary and final tests in terms of the magnitude of changes in the analyzed variables (deltas) of both studied groups, significant changes in favor of Nordic walking were noted in the duration of the exercise test (respectively: 1.13 vs. 0.63 min; $p = 0.002$), maximum oxygen consumption $VO_2$max (respectively: 4.37 vs. 2.33 ml; $p = 0.035$) and the distance covered on the treadmill (respectively: 59.71 vs. 39.34 m; $p = 0.045$). With regard to the other indicators of the exercise test (MET, resting and peak heart rate, resting and peak blood pressure), favorable changes were obtained, but they were not statistically significant.

Kukkonen-Harjula et al. (12) investigated the effectiveness of walking and Nordic walking among women aged 50–60, leading a sedentary lifestyle but with a normal BMI index. After the end of the 13-week training cycle (classes were conducted 4 times a week for 40 min), they showed an increase in the maximum oxygen consumption ($VO_2$max) in both groups (in the Nordic walking group by 2.5 ml/min/kg, in the group without poles by 2.6 ml/min/kg). In both groups, a reduction in the resting value and the exercise rate of heart contractions was also achieved. On the other hand, Mikalački et al. (20), examining the efficiency of older women (58.5 ± 6.90 years) participating in 3-month walking training with poles (3 times a week), obtained a result that also confirms its effectiveness. Based on the exercise tests

TABLE 4 Comparison of body mass composition indices before (1) after (2) training completion.

| Variable | CWG | | | NWG | | |
|---|---|---|---|---|---|---|
| | $\bar{X} \pm$ SD | Δ | *p* | $\bar{X} \pm$ SD | Δ | *p* |
| Fitness score 1 | 68.61 ± 6.30 | −1.21 | 0.581 | 68.20 ± 6.49 | −0.93 | 0.702 |
| Fitness score 2 | 67.40 ± 5.84 | | | 67.26 ± 6.68 | | |
| ΔCWG vs. ΔNWG | 0.543 | | | | | |
| VFA [cm$^{2]}$ 1 | 136.04 ± 33.74 | 2.27 | 0.834 | 134.37 ± 25.90 | 10.47 | 0.360 |
| VFA [cm$^2$] 2 | 138.31 ± 24.50 | | | 144.85 ± 35.11 | | |
| ΔCWG vs. ΔNWG | 0.121 | | | | | |
| Body mass [kg] 1 | 71.70 ± 13.81 | −1.47 | 0.759 | 70.34 ± 11.97 | 1.90 | 0.689 |
| Body mass [kg] 2 | 70.23 ± 12.27 | | | 72.24 ± 13.78 | | |
| ΔCWG vs. ΔNWG | 0.741 | | | | | |
| SMM [kg] 1 | 24.21 ± 3.06 | −0.86 | 0.476 | 23.62 ± 3.16 | 0.39 | 0.734 |
| SMM [kg] 2 | 23.35 ± 3.43 | | | 24.01 ± 3.14 | | |
| ΔCWG vs. ΔNWG | 0.532 | | | | | |
| BFM [kg] 1 | 27.20 ± 9.882 | 0 | 0.999 | 26.85 ± 8.13 | 1.34 | 0.688 |
| BFM [kg] 2 | 27.20 ± 7.815 | | | 28.20 ± 9.94 | | |
| ΔCWG vs. ΔNWG | 0.489 | | | | | |
| PBF [%] 1 | 0.98 ± 9.88 | 129.28 | 0.001 | 0.98 ± 0.04 | 133.29 | 0.001 |
| PBF [%] 2 | 130.26 ± 17.48 | | | 134.27 ± 27.53 | | |
| ΔCWG vs. ΔNWG | 0.989 | | | | | |
| ECW [%] 1 | 20.09 ± 2.35 | −7.91 | 0.001 | 19.64 ± 2.42 | −7.23 | 0.001 |
| ECW [%] 2 | 12.18 ± 1.62 | | | 12.40 ± 1.39 | | |
| ΔCWG vs. ΔNWG | 0.989 | | | | | |
| ICW [%] 1 | 12.61 ± 1.41 | 6.81 | 0.001 | 12.34 ± 1.48 | 7.60 | 0.001 |
| ICW. [%] 2 | 19.43 ± 2.62 | | | 19.94 ± 2.14 | | |
| ΔCWG vs. ΔNWG | 0.989 | | | | | |
| TBW [kg] 1 | 32.70 ± 3.75 | −1.09 | 0.460 | 31.987 ± 3.89 | 0.36 | 0.798 |
| TBW [kg] 2 | 31.61 ± 4.23 | | | 32.350 ± 3.79 | | |
| ΔCWG vs. ΔNWG | 0.345 | | | | | |

All data are presented as mean ± standard deviation and the difference (Δ, delta).
CWG, conventional walking group; NWG, Nordic walking group; VFA, visceral fat area; BFM, body fat mass; SMM, skeletal muscle mass; BFM, body fat mass; PBF, percent body fat; ICW, intracellular water; ECW, extracellular water; TBW, total body water.

performed before and after the training program, they observed a reduction in resting heart rate (84.93 vs. 73.42 bpm, $p = 0.001$), systolic and diastolic blood pressure (129.83/84.66 vs. 118.42/79.04 mmHg, $p = 0.000$) and increase in $VO_2$max (15.75 vs. 21.83 ml/kg/min, $p = 0.000$). The high effectiveness of walking training with poles was also confirmed in the research by Tschentscher et al. (21) and Fritschi et al. (10), achieving a similar effect. It is also worth mentioning the first studies assessing the effectiveness of walking and Nordic walking among women. They were conducted in 1992 at the University of Wisconsin-La Crosse in the United States. The training lasted 3 months (4 times a week for 30–45 min). In both studied groups, an increase in the level of $VO_2$max was observed, but the largest (8%) was in the Nordic walking group.

## Body weight composition

In both groups there was a significant increase in the percentage of adipose tissue in the body and the percentage of intracellular water, and a significant decrease in the percentage of extracellular water. There was also an increase in skeletal muscle mass in the Nordic walking group. With regard to the other components, the changes turned out to be insignificant, and in some cases, such as visceral obesity, the expected training effect turned out to be the opposite. The only explanation for such surprising results may be the lack of discipline associated with the diet during the entire training program. Before starting the training cycle, all the women were instructed about the dietary recommendations, indications and contraindications for eating certain products, the time of eating meals and their volume. During an interview conducted after the end of the program, some women admitted that they did not always follow the recommended diet. Perhaps the obtained results were influenced by the observation time, which in turn would be confirmed by the Willmore study (22). He performed a meta-analysis of 53 studies on changes in body mass composition under the influence of physical training with and without changing the diet. He found that the 6-month period of increased physical activity caused a decrease in body weight by an average of 1.6 kg, a decrease in fat mass by an average of 2.6 kg and an increase in lean mass by 1.0 kg. In studies with a shorter follow-up period of up to 12 weeks, no or insignificant changes were observed. A similar meta-analysis was conducted

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TABLE 5 Correlation of BMI values with the results of the exercise test.

| Variable | Δ HRrest [beats/min] | Δ SBPrest [mmHg] | Δ DBPrest [mmHg] | Δ Duration [min] | Δ MET | Δ $VO_{2peak}$ [ml/kg/min] | Δ Distance [m] | Δ HRpeak [beats/min] | Δ SBPpeak [mmHg] | Δ DBPpeak [mmHg] |
|---|---|---|---|---|---|---|---|---|---|---|
| ΔBMI [kg/m$^2$] | −0.100 | −0.183 | 0.067 | −0.147 | −0.273 | 0.056 | −0.057 | −0.021 | −0.166 | 0.089 |

BMI, body mass index; HRrest, heart rate at rest; SBPrest, systolic blood pressure at rest; DBPrest, diastolic blood pressure at rest; MET, metabolic equivalent; $VO_2$ peak, peak oxygen consumption; HRpeak, peak heart rate; SBPpeak, peak systolic blood pressure; DBPpeak, diastolic blood pressure.

TABLE 6 Correlation of the values of body mass composition indices with the results of the exercise test.

| Variable | Δ HRrest [beats/min] | Δ SBPrest [mmHg] | Δ DBPrest [mmHg] | Δ Duration [min] | Δ MET | Δ $VO_{2peak}$ [ml/kg/min] | Δ Distance [m] | Δ HRpeak [beats/min] | Δ SBPpeak [mmHg] | Δ DBPpeak [mmHg] |
|---|---|---|---|---|---|---|---|---|---|---|
| ΔFitness score | −0.070 | 0.235 | −0.127 | 0.420 | 0.286 | 0.338 | 0.494 | 0.030 | 0.195 | −0.104 |
| ΔVFA [cm$^2$] | −0.060 | −0.192 | 0.085 | −0.225 | −0.266 | −0.098 | −0.142 | −0.039 | −0.252 | 0.104 |
| ΔBody mass [kg] | 0.029 | −0.083 | −0.096 | −0.166 | −0.241 | −0.050 | −0.097 | 0.110 | −0.224 | −0.066 |
| ΔSMM [kg] | 0.060 | 0.073 | −0.232 | 0.023 | −0.120 | 0.067 | 0.115 | 0.173 | −0.167 | −0.171 |
| ΔBFM [kg] | 0.006 | −0.183 | 0.015 | −0.267 | −0.286 | −0.123 | −0.229 | 0.045 | −0.215 | 0.029 |
| ΔPBF [%] | −0.100 | −0.184 | 0.066 | −0.147 | −0.272 | 0.055 | −0.056 | −0.021 | −0.166 | 0.088 |
| ΔECW [%] | 0.061 | 0.074 | −0.231 | 0.020 | −0.122 | 0.064 | 0.113 | 0.178 | −0.163 | −0.169 |
| ΔICW [%] | 0.036 | 0.075 | −0.205 | −0.023 | −0.123 | 0.051 | 0.077 | 0.160 | −0.221 | −0.195 |
| ΔTBW [kg] | 0.052 | 0.075 | −0.222 | 0.003 | −0.123 | 0.059 | 0.099 | 0.171 | −0.186 | −0.179 |

VFA, visceral fat area, BFM, body fat mass, SMM, skeletal muscle mass, BFM, body fat mass, PBF, percent body fat, ICW, intracellular water, ECW, extracellular water, TBW, total body water, HRrest, heart rate at rest, SBPrest, systolic blood pressure at rest DBPrest, diastolic blood pressure at rest, MET, metabolic equivalent, $VO_2$ peak, peak oxygen consumption, HRpeak, peak heart rate, SBPpeak, peak systolic blood pressure, DBPpeak, diastolic blood pressure.

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TABLE 7 Correlation of the BMI value with the results of the exercise test.

| Variable | Δ HRrest [beats/min] | Δ SBPrest [mmHg] | Δ DBPrest [mmHg] | Δ Time [min] | Δ MET | Δ $VO_{2peak}$ [ml/kg/min] | Δ Distance [m] | Δ HRpeak [beats/min] | Δ SBPpeak [mmHg] | Δ DBPpeak [mmHg] |
|---|---|---|---|---|---|---|---|---|---|---|
| ΔBMI [kg/m$^2$] | 0.077 | −0.149 | −0.130 | 0.439 | 0.626 | 0.222 | 0.442 | −0.241 | −0.241 | 0.098 |

BMI, body mass index; HRrest, heart rate at rest; SBPrest, systolic blood pressure at rest; DBPrest, diastolic blood pressure at rest; MET, metabolic equivalent; $VO_2$ peak, peak oxygen consumption; HRpeak, peak heart rate; SBPpeak, peak systolic blood pressure; DBPpeak, diastolic blood pressure.

TABLE 8 Correlation of body mass index values with results of the exercise test.

| Variable | Δ HRrest [beats/min] | Δ SBPrest [mmHg] | Δ DBPrest [mmHg] | Δ Time [min] | Δ MET | Δ $VO_{2max}$ [ml/kg/min | Δ Distance [m] | Δ HRmax [beats/min] | Δ SBPmax [mmHg] | Δ DBPmax [mmHg] |
|---|---|---|---|---|---|---|---|---|---|---|
| ΔFitness score | −0.093 | −0.105 | 0.144 | −0.355 | −0.392 | −0.158 | −0.347 | −0.091 | −0.078 | −0.062 |
| Δ VFA [cm$^2$] | 0.160 | 0.054 | −0.097 | 0.320 | 0.548 | 0.174 | 0.310 | −0.164 | −0.091 | 0.085 |
| Δ Body mass [kg] | 0.163 | −0.079 | −0.120 | 0.178 | 0.528 | 0.219 | 0.217 | −0.210 | −0.226 | 0.003 |
| Δ SMM [kg] | 0.151 | −0.143 | −0.074 | −0.125 | 0.317 | 0.155 | −0.052 | −0.284 | −0.289 | −0.090 |
| Δ BFM [kg] | 0.142 | −0.039 | −0.134 | 0.316 | 0.566 | 0.223 | 0.332 | −0.148 | −0.164 | 0.051 |
| Δ PBF [%] | 0.078 | −0.149 | −0.130 | 0.440 | 0.626 | 0.222 | 0.442 | −0.241 | −0.241 | 0.098 |
| Δ ECW [%] | 0.152 | −0.143 | −0.074 | −0.125 | 0.315 | 0.155 | −0.054 | −0.281 | −0.288 | −0.088 |
| Δ ICW [%] | 0.148 | −0.140 | −0.034 | −0.105 | 0.368 | 0.159 | −0.025 | −0.272 | −0.296 | −0.073 |
| Δ TBW [kg] | 0.151 | −0.142 | −0.059 | −0.118 | 0.335 | 0.157 | −0.043 | −0.279 | −0.292 | −0.083 |

VFA, visceral fat area; BFM, body fat mass, SMM, skeletal muscle mass; BFM, body fat mass; PBF, percent body fat; ICW, intracellular water; ECW, extracellular water; TBW, total body water; HRrest, heart rate at rest; SBPrest, systolic blood pressure at rest; DBPrest, diastolic blood pressure at rest; MET, metabolic equivalent; $VO_2$ peak, peak oxygen consumption; HRpeak, peak heart rate; SBPpeak, peak systolic blood pressure; DBPpeak, diastolic blood pressure.

by Wing (23). An analysis of 29 randomized trials in which obesity was treated with only a low-calorie diet, or only increased physical activity, or a combination of these, indicated that the combined use of diet and increased physical activity resulted in the greatest (beneficial) changes in body weight composition. Grigolett et al. (24) when assessing the effectiveness of NW training in relation to anthropological parameters and body composition, also found high effectiveness of this form of training. Comparing the body weight composition of physically active and inactive women, aged >50 years, they found significant differences, more favorable in the group of active women, in terms of the percentage of cellular mass, percentage of body water, percentage of adipose tissue mass, percentage of lean tissue mass and muscle mass expressed in kilograms and as a percentage, as well as basal metabolic rate. Moreover, they observed significant differences in the percentage of total body water, percentage of lean mass, and percentage of adipose tissue mass. Bullo et al. (25) carried out a meta-analysis of the influence of Nordic walking on the physical fitness, body composition and quality of life of the elderly, based on 15 studies. They observed favorable changes after the end of the training program of seniors. They concluded that Nordic walking can be considered a safe and accessible form of aerobic exercise for the elderly, capable of improving cardiovascular outcomes, muscle strength, body composition, balance ability and quality of life. Analyzing the effects of NW training in the treatment of overweight over 3 and 6 months from the start of training Muollo et al. also found a significant reduction in adipose tissue, BMI and aerobic capacity (26).

## Correlation of the level of exercise tolerance and body mass components

The study additionally analyzed the correlation of changes (delta) in the results of body mass composition with changes (delta) in the stress test indices for both studied groups. In the case of the walking group, no significant correlation was found, while in the Nordic walking group, a significant positive relationship was found between the BMI index and the increase in the duration of the exercise test, the metabolic cost of MET and the maximum oxygen consumption. In addition, there was a significant correlation between changes (delta) in body fat percentage, body fat mass, body weight, visceral obesity and fitness score with changes (delta) in metabolic cost associated with exercise testing, changes (delta) in body fat percentage, and the increase in the duration of the exercise test as well as the percentage changes (delta) in the content of adipose tissue and the increase in the distance covered during the test. Obtaining so many relationships between changes in body mass composition and changes in exercise test indicators in the Nordic walking group may result from the greater intensity of the form of training used than in the normal walking group, which in turn contributed to the improvement of exercise tolerance itself. Although in both analyzed groups a similar significant change was found in relation to the same body composition parameters (percentage of adipose tissue, external and intracellular water), the intensity of the training played a key role. Moreover, if we analyze the results in both studied groups, we find that the dynamics of changes in the body mass composition, despite the lack of statistical significance, was higher in the Nordic walking group than in the normal walking group. Therefore, it can be assumed that, as mentioned earlier, the training intensity had an influence on the obtained result of the studied dependencies.

To sum up, the studies conducted in the group of women >50 years of age confirmed the effectiveness of walking training, regardless of whether it was with or without poles. Both forms of activity had a similar effect on the improvement of exercise tolerance, lipid profile and body weight composition. When analyzing changes in body mass composition in relation to changes in exercise tolerance, the Nordic walking group achieved a more favorable result. Therefore, it seems that this form of activity would be the most appropriate for women over 50. However, it must be remembered that when recommending Nordic walking training, due to its specific nature, one should always take into account the indications and contraindications. Regardless of the results of the experiment, walking with or without poles should be recommended as a safe and widely accessible form of physical activity, especially in relation to the elderly. A properly prepared and conducted training program based on the assessment of exercise tolerance is a very important element of both secondary and primary prevention.

## Study limitations

The main limitation of the study was the relatively short observation period, with limited frequency and duration of training. It resulted from the program framework (schedule of classes) imposed by the University of the Third Age. As shown by the results obtained in other studies, this period was too short. Another limitation of the study was that the number of participants was too small (group I – 32 people, group II – 34 people), which could also have an impact on the statistical analysis of the results. One more and perhaps the most important factor influencing the course of the experiment should also be mentioned. Since all women were hospitalized before and after training in order to perform appropriate diagnostic tests, in order not to interfere with work in the wards, the number of participants had to be limited to the necessary minimum.

## Conclusions

In both studied groups, a similar level of significant changes in the same body mass indices (percentage of adipose tissue, percentage of intra- and extracellular water) was obtained. In the other components, the results were not significant.

A relationship between the change in the level of exercise tolerance and changes in the body mass composition was observed only in the Nordic walking group.

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Ethics statement

The studies involving humans were approved by Bioethical Committee of the Jerzy Kukuczka Academy of Physical Education in Katowice (No. 7/2011). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

## Author contributions

VK: Conceptualization, Funding acquisition, Project administration, Writing – review & editing. KD: Conceptualization, Data curation, Formal analysis, Writing – original draft. WA: Methodology, Project administration, Writing – review & editing. GK: Funding acquisition, Validation, Writing – original draft. NZ: Formal analysis, Supervision, Visualization, Writing – original draft. TG: Writing – original draft, Resources, Software. N-LA: Investigation, Methodology, Visualization, Writing – original draft.

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The 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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# Meeting the WHO physical activity guidelines and health-related quality of life of single parents in Ghana

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**Purpose:** Improving physical activity (PA) and health-related quality of life (HRQoL) is critically important for achieving the health-related sustainable development goal (SDG 3). However, data on the association between PA and HRQoL, particularly among single parents, are limited in low- and middle-income countries (LMICs). We examine the association between PA and HRQoL among single parents in Ghana and explore the modifying roles of sex, age, and spatial differences in this association.

**Methods:** Data on 627 single parents were obtained through a multi-stage stratified sampling technique. PA was assessed using the International Physical Activity Questionnaire-Short Form (IPAQ-SF). The EQ-5D-3L questionnaire was used to measure HRQoL. A hierarchical Ordinary Least Squares (OLS) regression models evaluated the hypothesized associations.

**Results:** PA was significantly associated with poor HRQoL even after accounting for all potential confounders ($B = -0.298$, SE = 0.132, $p < 0.05$). The association was further modified by sex ($B = -0.619$, SE = 0.206, $p < 0.01$) and age ($B = -0.062$, SE = 0.008, $p < 0.001$). Thus, the PA-HRQoL association was more pronounced among older and female single parents.

**Conclusion:** Physical activity was negatively associated with poor HRQoL. Sex and age differences modified the association. Promoting PA may reduce poor HRQoL among single parents.

KEYWORDS

**physical activity, quality of life, Ghana, single parents, sustainable development goals**

## 1 Introduction

Health-related quality of life (HRQoL) is conceived as a multidimensional construct encompassing an individual's or a group's perceived physical and mental health over time (1), including psychological, emotional, cultural orientation, and social aspects of life (2). Previous studies have investigated the determinants of HRQoL among individuals within the general population. For example, gender, place of residence, education, employment status, and smoking status have been identified as correlates of HRQoL (3–5). Studies have also examined the association between PA and HRQoL among populations (3, 6, 7). However, whether meeting the WHO PA requirements is associated with HRQoL among single parents in low- and middle-income countries is almost unknown (7).

Meeting the WHO PA guidelines is associated with numerous health benefits, including improved cardiovascular health (6), mental well-being (7), and reduced risk of chronic diseases (8) in various populations, including single parents (5). However, approximately 1 in 4 adults do not meet the global recommended levels of PA, and more than 80% of the world's adolescent population is insufficiently physically active (5). Indeed, research suggests that meeting moderate-to-vigorous levels of PA guidelines was significantly associated with improved overall HRQoL. For instance, a cross-sectional study of 7,518 community-dwelling older Chinese revealed that PA was significantly and positively associated with each HRQoL component (9). Using a sample of 5,537 adults (40–60 years) from a representative national survey in England, Anokye et al. (10) suggest that higher levels of PA are associated with better HRQoL. However, such studies are relatively scarce in LMICs. The well-being of single parents is a vital public health concern, especially in a low- and middle-income country like Ghana, where socio-economic difficulties are widespread. The number of single parents in Ghana is rapidly increasing, primarily due to rising rates of divorce, separation, and widowhood (11). Single parents often face unique stressors that adversely affect their HRQoL (12). Understanding and addressing these challenges is crucial for creating effective public health interventions. However, there is a significant dearth of data on the association between PA and HRQoL among single parents.

Moreover, the association between PA and HRQoL may be moderated by age, sex, and spatial differences. For instance, younger single parents may be more likely to present a higher HRQoL and may be more physically active than older single parents due to the negative health effects of aging (3–13). Considering sex differences, males may have greater odds of meeting PA guidelines and the subsequent improvements in HRQoL than their female counterparts due to societal expectations and safety concerns (4, 14, 15). Again, urban environments may offer more opportunities and facilities (e.g., gyms, parks, and organized sports) for PA participation than rural areas (16–18).

Single parents are often at a higher risk of poverty and social exclusion (12). While extant studies have emphasized on PA and HRQoL in general populations, our study specifically targets single parents—a group that is often overlooked in health research in SSA, especially Ghana (5, 9). The health and well-being of single parents is critical for the socio-economic stability of families and communities (12). Therefore, the current study aims to examine the association between meeting the WHO PA guidelines and HRQoL among single parents in Ghana. We also seek to explore the potential effect modification of this association by age, sex, and rural/urban differences. The novelty of this study lies in its dual focus on a specific vulnerable group while addressing a critical aspect of public health—PA—within the context of HRQoL. The significance of this study goes beyond academic contributions. The study may potentially influence public health policies and community programs aimed at enhancing the quality of life for single parents in Ghana and similar settings. By establishing a clear link between PA and HRQoL among single parents, this research could pave the way for future studies and interventions that promote healthier lifestyles across populations facing similar socio-economic problems.

# 2 Methods

## 2.1 The survey

This study utilized multi-stage stratified sampling. The Atwima Kwanwoma District was purposefully selected based on anecdotal evidence suggesting many single parents. The district was informally divided into Atwima and Kwanwoma and further categorized into urban and rural communities based on socioeconomic characteristics and development factors such as economic activities, road conditions, and health and educational infrastructure (11). A simple random sampling method was employed to select 12 communities (i.e., four urban and eight rural communities) from 64 communities in the district (19). The names of all communities were written on slips of paper, acknowledging the informal division of the district into Atwima and Kwanwoma, which is typically split into East and West.

Using a fishbowl selection method, where names of all communities were placed in a bowl and drawn randomly (20), six communities (four rural and two urban) were chosen from Atwima, and another six communities (four rural and two urban) were selected from Kwanwoma, making a total of 12 communities (four urban and eight rural). The larger number of rural communities (8) compared to urban ones (4) was due to the higher population in urban areas. A default prevalence rate of 50% (20), equivalent to 0.5, was used to estimate the number of single parents in the district, as specific data was unavailable. Using this prevalence rate, Fisher's sample size estimation formula was applied to determine the overall sample size for the study (21).

The minimum sample size was calculated with the following parameters: a 95% confidence interval (∝) of 1.96, a prevalence (P) of 50% or 0.5 (since the proportion of single parents aged ≥13 years is unknown), a margin of error (d) of 5% or 0.05, and considering 5% type 1 error and 15% type 2 error. Adjustments were made to account for anticipated non-responses and outliers, aiming to enhance the generalizability and robustness of the findings (22). Consequently, the final sample size was set at $N = 627$. The researchers developed a face-to-face interviewer-administered questionnaire, and five research assistants were trained to administer the questionnaire. The questionnaire is part of a broader household survey covering various topics like sleep problems, depression, anxiety, financial concerns, neighborhood attachment, self-rated health and happiness, social networks, and functional limitations. Data collection occurred over 3 months, from June to August 2023. Ethical approval was obtained from relevant authorities, and written informed consent was secured from all respondents.

Though being a purely quantitative study, a convenience sampling technique was used in reaching out to the respondents. This became necessary when we observed, during the pretesting of our research instruments, that not all households in the selected communities were single-parent households. Moreover, we met some single parents at their workplaces. Therefore, using a more appropriate sampling technique, like systematic sampling, was not feasible.

## 2.2 Ethical consideration

The study was carried out in accordance with the World Medical Association's Declaration of Helsinki's code of ethics for research involving human subjects. The study protocol was reviewed and approved by the Humanities and Social Sciences Research Ethics Committee (HuSSREC) at Kwame Nkrumah University of Science and Technology in Kumasi, Ghana (Ref number: HuSSREC/AP/111/VOL.1.). Additionally, written informed consent was obtained from each respondent. Respondents were assured of confidentiality and anonymity of the information they provide. They were also assured of their right to stop or refuse to respond to any question they were not comfortable with, without being penalized. Indeed, we sought permission and approval from the parents or guardians of a few minors who had less than 18 years during data collection. Moreover, in the Ghanaian context, one is considered an adult when he or she gives birth and assumes the responsibility of childcare.

## 2.3 Measures

### 2.3.1 PA

Physical activity was evaluated using the International Physical Activity Questionnaire-Short Form (IPAQ-SF) (23), a tool that measures PA over the past 7 days as part of daily activities. Globally, the IPAQ-SF has demonstrated good validity and reliability (7, 23). The IPAQ-SF uses the following values to analyze PA: Walking = 3.3 MET (Metabolic Equivalent of Task, a unit of caloric expenditure), Moderate PA = 4.0 MET, and Vigorous PA = 8.0 MET. The continuous score for each PA category is expressed as MET-minutes per week, calculated as MET level x minutes of activity per day × days per week. Thus, the total PA MET-minutes per week is determined by summing the METs from walking, moderate activity, and vigorous activity using the formula: the sum of Walking + Moderate activity + Vigorous activity MET-minutes per week scores (23). In this analysis, the PA score was dichotomized. Those scoring less than 600 MET-minutes of moderate-to-vigorous intensity PA were classified as not meeting the recommended PA guidelines (code = 1), while those scoring 600 or more MET-minutes were classified as meeting the recommended PA guidelines (code = 2) (7). The IPAQ-SF has been validated in the Ghanaian context (7).

### 2.3.2 HRQoL

Health-related quality of life was evaluated using the EQ-5D-3L questionnaire (20), which consists of five items covering mobility, self-care, daily activities, pain/discomfort, and restlessness. Each item was rated on a three-level scale: 1 for no problems, 2 for moderate problems, and 3 for severe problems. The total score ranges from 5 to 15, with higher scores indicating poorer HRQoL. The variable was dichotomized into high and low HRQoL, with scores from 5 to 8 representing high HRQoL and scores from 9 to 15 representing low HRQoL. This dichotomization was based on limited empirical evidence (20). Each component of the HRQoL variable was treated as a separate dependent variable and individually regressed on the independent variable. The EQ-5D-3L questionnaire has been validated in the Ghanaian context (24).

### 2.3.3 Moderating variables

Sex, age, and spatial variations were moderating variables. Sex was considered dichotomous. A single father was given a score of 1, while a single mother scored 2. Age was measured in years (for the purpose of stratification, it was categorized into a 14–45-year group and a 46–90-year group), while residential status was also dichotomous (rural/urban).

### 2.3.4 Covariates

Based on prior research, the analytic models were adjusted for demographic, socio-economic, lifestyle, and health-related variables (24, 25). These included socio-economic and demographic factors such as sex (male or female), residential status (rural or urban), support satisfaction, period of stay, educational attainment (measured in number of years spent in school), work status (unemployed, employed or retired), income levels (in Ghana Cedis), financial hardship (yes/no), living arrangement (i.e., living with others apart from children, yes/no), social network (Lubben Social Network Scale – 6 Item Version), economic status, food insecurity (yes/no), and religious attendance level. Additional factors included current smoking status (no = 0/yes = 1), alcohol intake (no = 0/yes = 1), depression, sleep quality, anxiety, and NHIS status (yes or no).

## 2.4 Statistical analyses

The statistical analysis was conducted using SPSS v25 (SPSS, Inc., IBM, Armonk, NY, United States). The statistical significance was determined as the *p*-value of <0.05. Sample characteristics are first displayed as stratified by the meeting of WHO PA guidelines (<600 MET min; ≥600 MET min) and HRQoL (low and high). The difference in sample characteristics was tested using Student's *t*-tests and Chi-squared tests for continuous and categorical variables. In the second step, hierarchical OLS regression models were conducted to examine the link between meeting PA guidelines and HRQoL. We further performed interaction analysis (i.e., Sex × PA, residence × PA, and age × PA) to determine the moderation role of age, sex, and residence in the association of PA and HRQoL.

Model 1 was the unadjusted model. Model 2 included Model 1 and adjusted for age and sex. Model 3 included Model 2 and further adjusted for alcohol, residence, employment, household size, living arrangement, NHIS, education, social network, age, sex, sleep quality, depression, financial hardship, economic status, chronic conditions, and anxiety. Model 4 included Model 3 and the interaction term, PA × sex. Model 5 included Model 3 and the interaction term, PA × age. Model 6 included Model 3 and the interaction term, PA × residential status. Third, the OLS regression estimating the association between PA and the various components of HRQoL was conducted. Each component of the HRQoL variable was treated as separate dependent variables as they were individually regressed on PA and other covariates (independent variables). Lastly, OLS regression models estimating the association between meeting PA guidelines stratified by age and sex groups were also conducted. Stratification by residence was not included because the interaction analysis was not statistically significant.

# 3 Results

## 3.1 Sample characteristics

A total of 627 individuals were included in the current study. The characteristics of this analytic sample are shown in Table 1. The

TABLE 1 Demographic and health-related characteristics of the sample – overall and by meeting PA guidelines and health-related quality of life (HRQoL).

| | Overall | | Not meeting PA | | Meeting PA | | *p*-value | Statistic | Low HRQoL | | High HRQoL | | *p*-value | Statistic |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Variable | N/M | (%)/SD | N/M | (%)/SD | N/M | (%)/SD | | | N/M | (%)/SD | N/M | (%)/SD | | |
| Age (years) (M ± SD) | 44.95 | (14.6) | 60.16 | (12.36) | 39.70 | (11.35) | <0.001 | 0.66 | 61.35 | (11.99) | 41.35 | (12.56) | <0.001 | 0.031 |
| Sex | | | | | | | <0.05 | 4.076 | | | | | <0.001 | 11.364 |
| Female | 422 | (67.3) | 98 | (15.6) | 324 | (51.7) | | | 92 | (14.7) | 330 | (52.6) | | |
| Male | 205 | (32.7) | 63 | (10.0) | 142 | (22.6) | | | 22 | (3.5) | 183 | (29.2) | | |
| Residential type | | | | | | | <0.05 | 4.708 | | | | | >0.05 | 0.21 |
| Rural | 342 | (54.5) | 76 | (12.1) | 266 | (42.4) | | | 60 | (9.6) | 282 | (45) | | |
| Urban | 285 | (45.5) | 85 | (13.6) | 200 | (31.9) | | | 54 | (8.6) | 231 | (36.8) | | |
| Personal income (M ± SD) | 1938.28 | (904.46) | 2118.01 | (1038.8) | 1876.18 | (845.54) | <0.005 | 15.290 | 1914.04 | (819.66) | 1943.66 | (922.909) | >0.05 | 3.233 |
| Years of education (M ± SD) | 9.47 | (4.00) | | | | | | | | | | | <0.001 | 39.36 |
| Employment status | | | | | | | <0.001 | 118.09 | | | | | | |
| Employed | 450 | (71.8) | 76 | (12.1) | 374 | (59.6) | | | 62 | (9.9) | 388 | (61.9) | | |
| Unemployed | 137 | (21.9) | 48 | (7.7) | 89 | (14.2) | | | 31 | (4.9) | 106 | (16.9) | | |
| Retired | 40 | (6.4) | 37 | (5.9) | 3 | (0.5) | | | 21 | (3.3) | 19 | (3.0) | | |
| Financial hardship (M ± SD) | 3.25 | (2.23) | 2.78 | (2.36) | 3.42 | (2.17) | <0.01 | 3.78 | 3.62 | (2.22) | 3.17 | (2.23) | >0.05 | 0.246 |
| Smoking status | | | | | | | >0.05 | 0.413 | | | | | >0.05 | 0.36 |
| No | 611 | (97.4) | 158 | (25.2) | 453 | (72.2) | | | 112 | (17.9) | 499 | (79.6) | | |
| Yes | 16 | (2.6) | 3 | (0.5) | 13 | (2.1) | | | 2 | (0.3) | 14 | (2.2) | | |
| Alcohol status | | | | | | | >0.05 | 0.450 | | | | | >0.05 | 0.03 |
| No | 580 | (92.5) | 147 | (23.4) | 433 | (69.1) | | | 105 | (16.7) | 475 | (75.8) | | |
| Yes | 47 | (7.5) | 14 | (2.2) | 33 | (5.3) | | | 9 | (1.4) | 38 | (6.1) | | |
| Depressive symptoms (M ± SD) | 15.61 | (3.88) | 14.70 | (4.22) | 15.92 | (3.71) | <0.005 | 8.02 | 16.56 | (3.95) | 15.39 | (3.84) | <0.005 | 0.12 |
| Anxiety symptoms (M ± SD) | 8.88 | (3.82) | 7.9 | (3.82) | 9.19 | (3.82) | <0.005 | 8.113 | 9.83 | (3.81) | 8.67 | (3.80) | <0.005 | 0.11 |
| Sleep problems (M ± SD) | 3.15 | (0.66) | 3.44 | (0.59) | 3.04 | (0.65) | <0.01 | 10.21 | 3.59 | (0.55) | 3.04 | (0.64) | <0.001 | 10.88 |
| Chronic condition (M ± SD) | 1.10 | (1.35) | 2.30 | (1.49) | 0.64 | (0.98) | <0.001 | 49.31 | 2.56 | (1.55) | 0.74 | (1.04) | <0.001 | 40.88 |
| Functional limitation (M ± SD) | 0.15 | (0.62) | 0.54 | (1.13) | 0.01 | (0.08) | <0.001 | 626.60 | 0.02 | (0.15) | 0.73 | (1.27) | <0.001 | 1033.23 |
| Food insecurity (M ± SD) | 5.36 | (2.20) | 4.93 | (2.51) | 5.52 | (2.06) | <0.05 | 12.963 | 6.46 | (1.78) | 5.12 | (2.21) | <0.001 | 8.16 |
| Social network (M ± SD) | 8.32 | (6.44) | 10.72 | (6.37) | 7.48 | (6.26) | <0.001 | 0.260 | 7.97 | (6.14) | 8.40 | (6.51) | >0.05 | 0.022 |
| Religious attendance (M ± SD) | 2.64 | (0.87) | 2.70 | (0.79) | 2.62 | (0.89) | >0.05 | 4.80 | 2.72 | (0.84) | 2.6 | (0.87) | >0.05 | 0.778 |

N is the total population; M is the mean score; SD is the standard deviation; HRQoL is the health-related quality of life; PA is physical activity. The *P*-value is based on either ordinal $\chi^2$ tests or independent *t*-test.



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average age was 45.0 (SD = 14.7) years, ranging from 14 to 85 years, and 67.3% were females. The majority of the sample lived in rural communities (54.5%), were gainfully employed (71.8%), and neither smoked (97.4%) or consumed alcohol (92.5%). On average, every participant had schooled for 9.5 (SD = 4.0) years while the mean monthly income was approximately 1938.28 (SD = 904.46) Ghana Cedis (US$ 140). Moreover, the mean physical activity, social network, and number of chronic physical conditions scores were 330.79 (SD = 420.83), 8.32 (SD = 6.44), and 1.07 (SD = 1.35), respectively. A Pearson's Chi-square test and Student $t$-test indicated that individuals who did not meet the WHO PA guidelines with <600 MET min of PA significantly had much worse scores for functional limitations ($F = 626.60$, $p < 0.001$), chronic physical conditions ($F = 49.31$, $p < 0.001$), sleep problems ($F = 10.21$, $p < 0.01$), anxiety ($F = 8.113$, $p < 0.005$), and depression ($F = 8.02$, $p < 0.005$) compared to those who met the WHO PA guidelines with ≥600 MET min of PA. Similarly, those who had low HRQoL had worse scores for functional limitations ($F = 1033.23$, $p < 0.001$), chronic conditions ($F = 40.88$, $p < 0.001$), sleep problems ($F = 10.88$, $p < 0.001$), depression ($F = 0.12$, $p < 0.005$) and anxiety ($F = 0.11$, $p < 0.005$) compared to those who had high HRQoL. Additionally, the Chi-square results showed that there was a significant association at a 5% significance level between sex and PA ($\chi^2 = 4.076$, $p < 0.05$), sex and HRQoL, ($\chi^2 = 11.364$, $p < 0.001$), residence and PA ($\chi^2 = 4.708$, $p < 0.05$). In addition, the independent $t$-test results revealed a statistically significant association between age and PA ($F = 0.66$, $p < 0.001$), age, and HRQoL ($F = 0.031$, $p < 0.001$).

### 3.2 Main regression and moderation analyses

The results of the associations between meeting WHO PA guidelines and HRQoL, estimated by hierarchical OLS regression models for the pooled sample, are detailed in Table 2. The crude model (Model 1) revealed a significant negative association between PA and low HRQoL ($B = -1.57$, SE = 0.14, $p < 0.001$). After adjusting for age and sex in Model 2, the effect size decreased, indicating a weaker negative association ($B = -0.505$, SE = 0.148, $p < 0.001$). In Model 3, which adjusted for socio-demographic, socio-economic, and health-related factors, the significant negative association persisted, though the effect size was further reduced ($B = -0.298$, SE = 0.132, $p < 0.05$). Models 4 and 5 demonstrated significant moderating effects of sex ($B = -0.619$, SE = 0.206, $p < 0.01$) and age ($B = -0.062$, SE = 0.008, $p < 0.001$) on the association between PA and low HRQoL. However, the moderating role of residence in Model 6 was not significant. Further, the OLS regression analysis of PA's impact on various HRQoL components (Table 3) showed substantial negative associations with pain/discomfort ($B = -0.143$, SE = 0.053, $p < 0.01$), usual activities ($B = -0.311$, SE = 0.040, $p < 0.001$), mobility ($B = -0.094$, SE = 0.047, $p < 0.05$), and self-care ($B = -0.109$, SE = 0.028, $p < 0.001$). Additionally, sex and age-stratified estimations of the association between PA and HRQoL (Table 4) revealed significant differences: males ($B = -0.967$, SE = 0.188, $p < 0.001$) and females ($B = -1.330$, SE = 0.147, $p < 0.001$), as well as between age groups (14–45 years: $B = -0.395$, SE = 0.193, $p < 0.05$) and (46–90 years: $B = -1.018$, SE = 0.177, $p < 0.001$). The analysis indicated that the negative association between PA and HRQoL was more pronounced among older adults and females.

## 4 Discussion

### 4.1 Main findings

Physical activity was significantly associated with decreased poor HRQoL, even after accounting for potential confounders. Additional analysis revealed a substantial negative association between PA and specific components of HRQoL, including pain/discomfort, usual activities, mobility, and self-care. The interaction analysis revealed a modifying effect of sex differences and age differences in the association of PA with poor HRQoL. Thus, the age and sex-stratified analysis showed that the association between PA and poor HRQoL was more pronounced among older adults and females. To our knowledge, this is the first study to provide insights into the link between PA and HRQoL among single parents in a LMIC context. This adds to our current knowledge mainly based on studies using data from high-income countries USA, China, Japan etc. Moreover, public health policies may leverage the findings of this study to create targeted health promotion programs such as community-based PA initiatives (e.g., keep fit clubs), family-oriented activities and integration of PA into health education.

### 4.2 Interpretation of findings

The results indicate a negative association between adherence to WHO PA guidelines and poor HRQoL among single parents in Ghana. Regular PA has been consistently linked to enhanced physical health, psychological well-being, and overall quality of life (3, 22, 26). Engaging in recommended PA levels appears to contribute positively to various aspects of HRQoL, including better physical functioning, reduced stress levels, and improved emotional resilience. This is consistent with previous studies investigating PA's association with HRQoL. For instance, a study in China by Hao et al. (3) revealed PA was positively associated with HRQoL among adults. Similarly, in a large population of Tehranian adults, Jalali-Farahani et al. (26) found levels of PA were significantly associated with most subscales of HRQoL in both men ($p < 0.05$) and women ($p < 0.01$).

The association between PA and HRQoL may be explained by a range of physiological, psychological, and socio-economic mechanisms (3). Physiologically, regular PA strengthens the heart, enhances blood circulation, and lowers the risk of heart disease (10). PA may improve cardiovascular health by enhancing heart and lung function, reducing blood pressure, improving blood lipid profiles and thereby enhancing health-related quality of life (6). Regular PA may also help regulate blood sugar levels and improve insulin sensitivity, reducing the risk of type 2 diabetes and metabolic syndrome (8). Furthermore, PA builds muscle strength and endurance, making everyday activities easier, leading to high HRQoL. Additionally, regular PA aids in maintaining a healthy weight, which is associated with a reduced risk of chronic physical conditions such as diabetes and hypertension (9).

The link between regular PA and psychological health are equally compelling. PA may reduce symptoms of anxiety and depression

TABLE 2 Hierarchical OLS regression models of the estimate of the association between meeting PA guidelines and health-related quality of life.

| | Model 1 | | Model 2 | | Model 3 | | Model 4 | | Model 5 | | Model 6 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Variable | *B* | (SE) | *B* | (SE) | *B* | (SE) | *B* | (SE) | *B* | (SE) | *B* | (SE) |
| Physical activity | −1.57 | (0.14)*** | −0.505 | (0.148)*** | −0.298 | (0.132)* | 0.719 | (0.363)* | 3.010 | (0.467)*** | 0.195 | (0.321) |
| Age | | | 0.058 | (0.004)*** | 0.040 | (0.005)*** | 0.039 | (0.005)*** | 0.145 | (0.015)*** | 0.039 | (0.005)*** |
| Sex (ref: male) | | | | | | | | | | | | |
| Female | | | 1.244 | (0.110)*** | 0.757 | (0.106)*** | 1.835 | (0.374)*** | 0.757 | (0.101)*** | 0.762 | (0.106)*** |
| Residential type (ref: rural) | | | | | | | | | | | | |
| Urban | | | | | 0.019 | (0.096) | 0.020 | (0.096) | −0.006 | (0.092) | 0.599 | (0.358) |
| Household size | | | | | −0.016 | (0.022) | −0.016 | (0.021) | 0.030 | (0.021) | −0.013 | (0.021) |
| Years of education | | | | | −0.043 | (0.013)** | −0.039 | (0.012)** | −0.040 | (0.012)*** | −0.043 | (0.012)*** |
| Employment (ref: unemployed) | | | | | | | | | | | | |
| Employed | | | | | 0.078 | (0.093) | 0.095 | (0.093) | 0.078 | (0.089) | 0.071 | (0.093) |
| Sleep quality | | | | | 0.268 | (0.080)*** | 0.266 | (0.079)*** | 0.255 | (0.076)*** | 0.272 | (0.079)*** |
| Economic status | | | | | −0.437 | (0.081)*** | −0.431 | (0.080)*** | −0.361 | (0.078)*** | −0.433 | (0.081)*** |
| NHIS | | | | | 0.113 | (0.110) | 0.115 | (0.109) | 0.066 | (0.105) | 0.110 | (0.110) |
| Social networks | | | | | −0.027 | (0.008)*** | −0.025 | (0.008)** | −0.026 | (0.008)*** | −0.027 | (0.008)*** |
| Alcohol status | | | | | 0.150 | (0.169) | 0.179 | (0.167) | 0.293 | (0.162) | 0.166 | (0.168) |
| Financial hardship | | | | | 0.075 | (0.025)** | 0.079 | (0.025)** | 0.080 | (0.024)*** | 0.074 | (0.025)** |
| Depressive symptoms | | | | | 0.006 | (0.017) | 0.003 | (0.017) | 0.012 | (0.016) | 0.005 | (0.017) |
| Chronic conditions | | | | | 0.354 | (0.044)*** | 0.369 | (0.044)*** | 0.318 | (0.043)*** | 0.355 | (0.044)*** |
| Anxiety symptoms | | | | | 0.004 | (0.018) | 0.007 | (0.018) | 0.003 | (0.017) | 0.002 | (0.018) |
| Physical activity × sex | | | | | | | −0.619 | (0.206)** | | | | |
| Physical activity × age | | | | | | | | | −0.062 | (0.008)*** | | |
| Physical activity × residence | | | | | | | | | | | −0.332 | (0.198) |
| Model information | | | | | | | | | | | | |
| Constant | 10.05 | (0.25)*** | 3.50 (0.453)*** | | 4.416 (0.646)*** | | 2.57 (0.88)** | | −1.925 (1.060) | | 3.571 (0.818)*** | |
| Adjusted pseudo $R^2$ | 0.167 | | 0.43 | | 0.599 | | 0.605 | | 0.632 | | 0.601 | |
| *F*-statistic | 126.69 | | 157.91 | | 55.443 | | 56.80 | | 63.590 | | 55.87 | |

B, Unstandardized regression coefficient; SE, robust standard error; NHIS, National health insurance scheme.
Model 1 Unadjusted model.
Model 2 included Model 1 and adjusted for age and sex.
Model 3 included Model 2 and further adjusted for alcohol, residence, employment, household size, living arrangement, NHIS, education, social network, age, sleep quality, depression, financial hardship, economic status, sex, chronic conditions and anxiety.
Model 4 included Model 3 and the interaction term, PA × sex.
Model 5 included Model 3 and the interaction term, PA × age.
Model 6 included Model 3 and the interaction term, PA × residential status.
$^*p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

through the release of endorphins, commonly known as "feel-good" hormones (7, 10). PA serves as a natural way to relieve stress, aiding individuals in managing daily challenges more effectively (7). Regular physical activity may mitigate the adverse effects of stress and improve mental health outcomes, which are particularly relevant for single parents who often face elevated levels of stress due to economic pressures, child-rearing responsibilities, and social isolation (12, 26, 27). Cognitively, PA may boost memory and learning abilities, which are essential for sustaining a good quality of life (10). This brain boost is partly due to its influence on mood-regulating neurotransmitters like serotonin and dopamine (25). Furthermore, participating in group fitness classes or team sports fosters social interactions, build friendships and support networks which provide a sense of belonging (26). That sense of belonging and connection is invaluable to HRQoL (26, 27).

The moderation analysis revealed that age and sex variations emerge as critical moderators that shape the magnitude and manifestation of the association between PA and HRQoL. The negative interaction term of age variations on the association of PA with poor HRQoL shows that the association was much stronger among younger single parents (14–45 years) compared with those aged (46 and above). Thus, as one ages, the effect of PA on HRQoL decreases. Age plays a crucial moderating role in the relationship between PA adherence and HRQoL. Younger single parents, typically more active and energetic, may experience greater benefits in terms of improved mood, energy levels, and stress reduction from regular

TABLE 3 OLS regression models estimating the association between meeting PA guidelines and specific components of poor health-related quality of life.

| Variable | Restlessness | | Pain/ discomfort | | Usual activities | | Mobility | | Self-care | |
|---|---|---|---|---|---|---|---|---|---|---|
| | *B* | (SE) | *B* | (SE) | *B* | (SE) | *B* | (SE) | *B* | (SE) |
| Physical activity | 0.047 | (0.061) | −0.143 | (0.053)** | −0.311 | (0.040)*** | −0.094 | (0.047)* | −0.109 | (0.028)*** |
| Age | −0.004 | (0.002) | 0.012 | (0.002)*** | 0.016 | (0.002)*** | 0.025 | (0.002)*** | 0.007 | (0.001)*** |
| Sex (ref: male) | | | | | | | | | | |
| Female | 0.208 | (0.053)*** | 0.150 | (0.046)*** | 0.150 | (0.035)*** | 0.272 | (0.041)*** | 0.040 | (0.025) |
| Residential type (ref: Rural) | | | | | | | | | | |
| Urban | −0.095 | (0.045)* | 0.066 | (0.039) | −0.030 | (0.030) | 0.035 | (0.042) | 0.002 | (0.021) |
| Sleep problems | 0.128 | (0.039)*** | 0.079 | (0.034)* | 0.020 | (0.026) | 0.016 | (0.030) | 0.014 | (0.018) |
| Ethnic background | 0.009 | (0.019) | −0.001 | (0.017) | 0.000 | (0.013) | 0.043 | (0.015)** | −0.011 | (0.009) |
| Years of education | −0.018 | (0.006)** | −0.019 | (0.005)*** | −0.001 | (0.004) | −0.003 | (0.005) | −0.001 | (0.003) |
| Economic status | −0.075 | (0.038)* | −0.113 | (0.033)*** | −0.081 | (0.025)*** | −0.096 | (0.029)*** | −0.085 | (0.018)*** |
| Religious attendance | 0.005 | (0.017) | −0.037 | (0.014)* | −0.033 | (0.011)** | −0.034 | (0.013)** | −0.036 | (0.008)*** |
| Social networks | −0.020 | (0.004) | −0.001 | (0.003) | −0.006 | (0.003)* | −0.004 | (0.003) | −0.004 | (0.002)* |
| Living arrangement | −0.011 | (0.051) | 0.072 | (0.044) | −0.035 | (0.034) | 0.037 | (0.039) | −0.039 | (0.024) |
| Employment | 0.011 | (0.045) | −0.005 | (0.039) | 0.005 | (0.030) | −0.011 | (0.035) | 0.034 | (0.021) |
| Alcohol | 0.146 | (0.083) | 0.005 | (0.072) | −0.044 | (0.054) | −0.026 | (0.064) | −0.046 | (0.038) |
| Depressive symptoms | 0.010 | (0.008) | 0.000 | (0.007) | 0.003 | (0.005) | 0.01 | (0.006) | 0.003 | (0.004) |
| Anxiety symptoms | 0.029 | (0.008)*** | 0.022 | (0.007)** | −0.012 | (0.006)* | −0.008 | (0.006) | −0.012 | (0.004)** |
| Model information | | | | | | | | | | |
| Constant | 1.064 | (0.294)*** | 1.411 (0.255)*** | | 1.322 (0.193)*** | | 0.330 (0.227) | | 1.340 (0.137)*** | |
| Adjusted pseudo $R^2$ | 0.343 | | 0.352 | | 0.479 | | 0.509 | | 0.274 | |
| *F*-statistic | 22.62 | | 23.46 | | 39.066 | | 43.801 | | 16.607 | |

B, unstandardized regression coefficient; SE, robust standard error.
All models were adjusted for age, sex, alcohol, employment, residence, living arrangement, religion, social network, education, social network, age, depression, economic status, sex, and anxiety.
*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

physical activity, thereby leading to higher HRQoL (3). Moreover, age-related declines in muscle mass (sarcopenia), bone density (osteoporosis), cardiovascular health and the fear of injury can make certain activities more difficult or even dangerous (28). Beyond the physical, older adults might grapple with the loss of peers, chronic health conditions impacting their mental well-being, or even societal ageism (stereotypes), all of which can affect their willingness to embrace an active lifestyle (3). This aligns with existing studies. For example, Bélanger et al. (28) suggest that PA adherence is greater for young adults (16–24 years: men = 27%; women = 21%) than older adults (65+ years: 12%; 11%). Etxeberria et al. (13) also found that the oldest old had a poorer HRQoL in both physical and mental dimensions. However, an interaction analysis from Hao et al. (3) indicated that the relationship between PA and HRQoL was significantly different across young, middle-aged, and older Chinese adults ($p < 0.05$), revealing that older adults with the sufficient PA (coefficient = 0.090, 95%CI: [0.081, 0.100]) and active PA (coefficient = 0.057, 95%CI: [0.043, 0.072]) had significantly higher HRQoL compared with young and middle-aged groups.

The interaction analysis also revealed a negative modifying effect of sex differences in the association of PA and low HRQoL. The results suggest that PA has a differential association with HRQoL based on sex. The current study reveals that while physical activity positively influences HRQoL in both sexes, the magnitude of this benefit is higher in males. Empirical studies show that males and females have different physiological responses to physical activity, which might influence how physical activity affects their HRQoL (15). Biologically, women undergo hormonal changes throughout their lives. For women, hormonal fluctuations throughout their lifespan – menstruation, pregnancy, and menopause – can significantly influence energy levels, mood, and physical performance, thus impacting their perception of PA benefits (4). Furthermore, differences in body composition – women generally having a higher percentage of body fat and lower muscle mass than men – can influence which types of activity they find most beneficial or enjoyable (14). Again, cultural and societal expectations regarding physical activity may differ between sexes as males might be more encouraged or expected to engage in physical activity and thus might derive greater psychological and social benefits from such engagement (7). Furthermore, the type and intensity of physical activity that males and females typically engage in may differ, potentially leading to different impacts on HRQoL. For instance, males might participate more in high-intensity or team sports, which could have stronger effects on improving HRQoL (14). On the other hand, Ji et al. (15) suggest that women,

TABLE 4 OLS regression models estimating the association between meeting PA guidelines stratified by age and sex groups.

| Variable | 14–45 year group | | 46–90 year group | | Males | | Females | |
|---|---|---|---|---|---|---|---|---|
| | *B* | (SE) | *B* | (SE) | *B* | (SE) | *B* | (SE) |
| Physical activity | −0.395 | (0.193)* | −1.018 | (0.177)*** | −0.967 | (0.188)*** | −1.330 | (0.147)*** |
| Residential type (ref: Rural) | | | | | | | | |
| Urban | −0.045 | (0.096) | 0.288 | (0.179) | 0.322 | (0.157)* | 0.025 | (0.121) |
| Support satisfaction | 496 | (0.089)*** | 0.137 | (0.091) | 0.382 | (0.102)*** | 0.003 | (0.075) |
| Period of stay | −0.001 | (0.003) | 0.015 | (0.004)** | 0.010 | (0.004)* | 0.020 | (0.003)*** |
| Years of education (ref: never) | −0.058 | (0.013)*** | −0.063 | (0.021)** | −0.089 | (0.021)*** | −0.045 | (0.015)** |
| Food insecurity | 0.232 | (0.030)*** | 0.381 | (0.048)*** | 0.229 | (0.047)*** | 0.334 | (0.036)*** |
| Sleep quality | 0.285 | (0.073)*** | 0.618 | (0.179)*** | 0.321 | (0.135)* | 0.450 | (0.097)*** |
| Economic status | −0.075 | (0.083) | −0.516 | (0.167)** | −0.369 | (0.166)* | −0.073 | (0.103) |
| Social networks | 0.001 | (0.008) | −0.007 | (0.017) | 0.008 | (0.012) | 0.000 | (0.011) |
| Employment | 0.034 | (0.110) | 0.095 | (0.145) | 0.315 | (0.171) | 0.188 | (0.113) |
| Financial hardship | −0.004 | (0.025) | −0.002 | (0.056) | −0.023 | (0.054) | −0.018 | (0.033) |
| Religious attendance | 0.029 | (0.031) | −0.138 | (0.068)* | −0.113 | (0.057)* | −0.022 | (0.044) |
| Depressive symptoms | −0.031 | (0.017) | 0.016 | (0.030) | −0.024 | (0.031) | −0.041 | (0.021)* |
| Anxiety symptoms | 0.067 | (0.016)*** | −0.043 | (0.036) | 0.102 | (0.035)** | −0.002 | (0.022) |
| Model Information | | | | | | | | |
| Constant | 4.385 | (0.618)*** | 6.598 | (1.165)*** | 5.622 | (0.912)*** | 7.145 | (0.713)*** |
| Adjusted pseudo $R^2$ | 0.465 | | 0.558 | | 0.582 | | 0.539 | |
| *F*-statistic | 22.563 | | 25.531 | | 21.106 | | 35.756 | |

B, unstandardized regression coefficient; SE, robust standard error.
All models were adjusted for support satisfaction, employment, residence, period of stay, religion, education, social network, depression, financial hardship, economic status, food insecurity, sleep quality and anxiety.
$^*p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

compared with men, derived greater gains in all-cause and cardiovascular mortality risk reduction from equivalent doses of leisure-time PA.

## 4.3 Implications for policy, practice, and research

The findings from this study, pending future longitudinal research, highlight the need for policies and interventions that promote the development of age and sex-specific PA programs. For example, younger single parents may benefit from high-intensity and time-efficient exercises, while older single parents might need low-impact and flexibility-focused activities like stretching, dancing and swimming. Programs may also consider the different time constraints, safety concerns, and social support systems needed for both males and females. Economic barriers may hinder single parents from engaging in regular PA. Policies by state and non-governmental agencies that provide subsidies or financial incentives for gym memberships, fitness classes, or sports participation may enhance access and adherence to PA. Again, health practitioners may promote PA options that may be easily integrated into the daily routines of single parents. Recommendations could include walking, home-based exercises, or family-oriented PA. Longitudinal research may provide insights into the long-term effects of meeting WHO PA guidelines on the HRQoL of single parents, highlighting the sustainability and effectiveness of various interventions.

## 4.4 Strengths and limitations

This study is among the few to investigate the relationship between PA and HRQoL, and it is the first to explore how age and sex differences moderate this association, specifically among single parents in Ghana. Given the limited information on PA among single parents in Ghana, the findings from this study could serve as a valuable baseline for future research. The key variables in the study were assessed using validated scales known for their robust reliability and content validity. Additionally, various potential confounders were controlled to enhance the validity of the results. Despite these strengths, the study has limitations. The cross-sectional design of the research limits the ability to establish causal relationships. Therefore, future studies may use a longitudinal design to draw causal conclusions. The reliance on retrospective self-reporting in the questionnaire may introduce recall and reporting biases. Again, future studies may consider clinical assessments of HRQoL to strengthen the validity of the findings. Nonetheless, self-reporting remains a practical method for capturing respondents' subjective evaluations of their HRQoL.

# 5 Conclusion

PA was negatively associated with poor HRQoL among single parents in the LMIC contexts and the association was significantly modified by age and sex differences. These findings highlight the importance of considering age and sex differences when designing and implementing PA interventions to improve HRQoL. Tailoring interventions to address the specific needs and responses of various age and sex groups may enhance their effectiveness.

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Ethics statement

The studies involving humans were approved by Humanities and Social Sciences Research Ethics Committee (HuSSREC) at Kwame Nkrumah University of Science and Technology in Kumasi, Ghana (Ref number: HuSSREC/AP/111/VOL.1.). The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants' legal guardians/next of kin.

## Author contributions

OO-S: Conceptualization, Data curation, Formal analysis, Writing – original draft, Writing – review & editing. KA: Data curation, Writing – original draft, Writing – review & editing. SO-T: Data curation, Writing – original draft, Writing – review & editing. AH: Data curation, Writing – original draft, Writing – review & editing. RG: Conceptualization, Data curation, Formal analysis, Supervision, Writing – original draft, Writing – review & editing.

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## Conflict of interest

The 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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The authors declare that no Gen AI was used in the creation of this manuscript.

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# Effects of Taekwondo training on thigh muscle cross-sectional area, health-related physical fitness, HbA1c, and GLP-1 in sedentary older women

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**Background:** Sedentary lifestyles in older individuals are associated with reduced physical function and an increased risk of metabolic diseases such as type 2 diabetes. Physical exercise can enhance muscle mass, insulin sensitivity, and metabolic health. Taekwondo, a martial art that integrates both aerobic and resistance components, may improve strength, balance, and metabolic health in older individuals. This study investigated the effect of long-term Taekwondo training on thigh muscle cross-sectional area, health related physical fitness, and metabolic indicators in sedentary older women.
**Methods:** Seventeen participants (aged 65 years and older, sedentary time 8 h and more per day) were randomly assigned to a Taekwondo group ($n = 9$) and a control group ($n = 8$). Outcomes, including thigh muscle cross-sectional area, health-related physical fitness, Homeostatic Model Assessment for Insulin Resistance (HOMA-IR), and Glucagon-like peptide-1 (GLP-1) were measured before and after the Taekwondo program. The Taekwondo group underwent 60 min of training, three times per week for 12 weeks. Variable changes over time and between groups were analyzed using two-way repeated measures ANOVA performed for significant interactions.
**Results:** The Taekwondo group exhibited a significant reduction in body weight, body mass index, body fat, and mean arterial blood pressure ($p < 0.05$), as well as increased thigh muscle cross-sectional area, lean body mass and lower limb muscle mass ($p < 0.05$). Improvements in balance and gait speed, stride were observed ($p < 0.05$), indicating reduced fall risk and enhanced mobility. Laboratory analyses revealed reduced triglyceride and free fatty acids and elevated HDL-cholesterol and GLP-1 levels ($p < 0.05$). Increased thigh muscle cross-sectional area was inversely correlated with fasting glucose, insulin, and HOMA-IR, suggesting improved insulin sensitivity and glucose regulation.
**Conclusion:** Long-term Taekwondo training improved thigh muscle cross-sectional area, health-related physical fitness and insulin resistance markers in sedentary older women, providing evidence for its use as an effective intervention to promote metabolic health in this population.

KEYWORDS

**Taekwondo, thigh muscle cross-sectional area, health-related physical fitness, metabolic syndrome, insulin resistance, older women**

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# 1 Introduction

The global average life expectancy was 73.6 years in 2022 and is projected to increase to 78.1 years by 2050 (1). However, as life expectancy increases, the health of the older individual population has emerged as a significant social issue and is recognized as a primary factor contributing to a decline in quality of life (2).

A sedentary lifestyle has a deleterious impact on the general health of older individuals (3, 4). Recent studies have also demonstrated that sedentary behavior negatively impacts thigh muscle cross-sectional area (CSA), leading to accelerated muscle atrophy and reduced functional capacity (5, 6). This is also, associated with an increased risk of metabolism-related conditions such as insulin resistance, metabolic syndrome, and type 2 diabetes, musculoskeletal conditions such as knee pain, sarcopenia and osteoporosis (7–9). In contrast, individuals who engage in reduced sedentary behavior, light physical activities, or simple muscle-strengthening exercises have been reported to exhibit superior health outcomes (10–13). More importantly, exercise can optimize these effects, which is crucial in reducing insulin resistance and preventing metabolic syndrome in older individuals (14, 15). Addressing these issues through targeted exercise interventions is essential for maintaining independence and overall well-being in aging populations.

Aerobic and anaerobic exercise have been independently demonstrated to enhance insulin sensitivity and facilitate glucose homeostasis, contributing to improved glycated hemoglobin (HbA1c) levels (16–18). Furthermore, exercise-induced increases in glucagon-like peptide-1 (GLP-1) levels play a significant role in improving insulin resistance (19). These changes have beneficial effects on muscle mass and insulin resistance, which contribute to overall metabolic health.

Thigh muscle mass is a crucial indicator of physical function and health status in older individuals, as it is directly associated with overall health (20). Thigh muscles comprise approximately 50%–80% of total body muscle mass and are essential for maintaining overall health, balance, and gait stability (21). In older adults, a reduction in thigh muscle mass is associated with an elevated risk of falls, diminished strength, increased prevalence of chronic disease, insulin resistance, and diminished quality of life (8, 22). Exercise that increases thigh muscle mass is effective in addressing these issues, thereby enhancing the overall physical function of older individuals (23).

Taekwondo, a widely accessible martial art in Korea, confers advantageous effects on physical function, and body composition in older individuals (24–27). As a combined aerobic and anaerobic exercise, Taekwondo, can contribute to improvements not only in strength and balance, but also cardiorespiratory endurance (24, 25, 28). The dynamic movements, including kicks, postural shifts, and coordinated footwork, provide significant muscle engagement that stimulates strength gains, particularly in the lower body (29).

Consequently, this can help prevent and improve the risk factors for sarcopenia (30), thus promoting the overall health of older individuals. The present study aims to assess the effects of regular and long-term Taekwondo training on thigh muscle CSA, health-related physical fitness, HbA1c, and GLP-1 levels in sedentary older women, providing valuable insights into the potential of martial arts as a multifaceted approach to healthy aging.

# 2 Materials and methods

## 2.1 Study participants

The participants were female residents aged 65 years or older from Busan city, Republic of Korea, who had no limitations in physical activity by a physician. A total of 26 participants were recruited and randomly assigned to either the Taekwondo training group ($n = 13$) or a control group ($n = 13$) using simple randomization via a computer-generated random sequence (https://www.ranmomizer.org).

Sedentary time was assessed using a wrist-worn PA monitor (Polar Active, Polar Electro, Finland), which participants were instructed to wear continuously for one week prior to the intervention. To classify sedentary behavior, an energy expenditure threshold of <1.5 METs was applied, following established guidelines for sedentary behavior assessment (31).

In the final analysis, 17 participants were included, while eight were excluded due to sedentary time non-eligibility ($n = 2$), relocation ($n = 1$), medical conditions ($n = 1$), attendance below 95% of the scheduled sessions ($n = 4$), and loss to follow-up ($n = 1$). Consequently, the analysis was conducted using data from 17 participants who fully adhered to the intervention and assessments, with 9 in the Taekwondo group and 8 in the control group. Participants who remained in the study attended at least 95% of the scheduled sessions. No serious injuries were reported during the intervention; however, some participants experienced minor discomfort, such as muscle soreness. Participants taking medication were instructed to maintain their usual lifestyle, including diet and physical activity habits, to ensure consistency. Baseline characteristics of the study participants are presented in Table 1.

This study was conducted in accordance with the principles of the Declaration of Helsinki and approved by the Institutional Review Board of D University (IRB No. 2-1040709-AB-N-01-201904-HR-022-04). Written informed consent was obtained from all participants.

## 2.2 Measurement of body composition

Body composition was evaluated using a body composition analyzer (VENUS 5.5, Jawon Medical Co., Korea) to ascertain

Abbreviations
ACSM, American college of sports medicine's; ASM, appendicular skeletal muscle mass; BMI, body mass index; CSA, cross-sectional area; FBG, fasting blood glucose; GLP-1, glucagon-like peptide-1; HbA1c, glycated hemoglobin; HDL-C, high-density lipoprotein cholesterol; HOMA-IR, homeostasis model assessment for insulin resistance; HRPF, health-related physical function; LBM, lean body mass; LDL-C, low-density lipoprotein cholesterol; LLM, lower limb muscle mass; MAP, mean arterial pressure; RPE, rating of perceived exertion; SLST, single-leg stance test; SPPB, short physical performance battery; TG, triglyceride; TUG, timed up-and-go; WHR, waist-hip ratio.

TABLE 1 Baseline characteristics of subjects.

| Variable | Taekwondo ($n$ = 9) | Control ($n$ = 8) | $p$-value |
|---|---|---|---|
| Age (years) | 73.00 ± 5.68 | 71.88 ± 4.32 | 0.743 |
| Body height (m) | 1.49 ± 0.02 | 1.49 ± 0.06 | 0.963 |
| Body mass (kg) | 58.89 ± 6.68 | 54.95 ± 4.38 | 0.200 |
| BMI (kg/m$^2$) | 26.54 ± 2.94 | 24.91 ± 2.25 | 0.236 |
| LBM (kg) | 33.31 ± 3.57 | 31.88 ± 3.09 | 0.370 |
| Body fat (%) | 43.27 ± 4.13 | 41.84 ± 5.49 | 0.541 |
| Waist circumference (cm) | 92.36 ± 6.68 | 90.05 ± 6.26 | 0.370 |
| WHR | 0.91 ± 0.04 | 0.94 ± 0.04 | 0.200 |
| Lower limb muscle mass (kg) | 9.69 ± 1.12 | 9.58 ± 1.14 | 0.673 |
| ASM (kg) | 13.17 ± 1.53 | 12.85 ± 1.42 | 0.606 |
| MAP (mmHg) | 106.56 ± 13.81 | 103.21 ± 9.59 | 0.370 |

Values are represented as mean ± standard deviation.
$p$-values were analyzed by Mann–Whitney $U$ test.
BMI, body mass index; LBM, lean body mass; WHR, waist-hip ratio; LLM, lower limb muscle mass; ASM, appendicular skeletal muscle mass; MAP, mean arterial pressure.

height, weight, lean body mass (LBM), and percent body fat. Waist and hip circumferences were measured with a Martin-type measuring tape, and the waist-hip ratio (WHR) was calculated using the following formula: waist circumference divided by hip circumference. Blood pressure was determined using a mercury-free sphygmomanometer (CK-E301, Chin Kow Medical Instrument Co., Ltd., Taiwan), and mean arterial pressure (MAP) was calculated according to the formula MAP = diastolic blood pressure + [(systolic blood pressure − diastolic blood pressure)/3], as previously reported (32).

## 2.3 Thigh muscle cross-sectional area

The thigh muscle CSA was evaluated via computed tomography (CT) using a CT Max II scanner (General Electric Co., USA). The scan was conducted in a transverse plane at the umbilicus level, specifically crossing the midpoint between the upper border of the patella and the greater trochanter. The mass of the thigh muscles was defined by regions with Hounsfield numbers ranging from −49 to +100, as described by Choi et al. (33).

## 2.4 Health-related physical fitness

HRPF was assessed using a set of physical fitness tests, including hand grip strength (34), the 2-minute walk test (35), the open-eyed single-leg stance test (SLST) (36), the timed up-and-go (TUG) test (37), the 4-m gait speed test (38), maximal stride length (39), and the short physical performance battery (SPPB) (40).

## 2.5 Blood collection and laboratory assays

Blood samples were collected and analyzed under standardized procedures. To minimize any circadian rhythm variations, all blood samples were collected in the morning hours (between 08:00 and 11:00 h). Participants were instructed to fast for at least 10–12 h before sample collection. Upon arrival at the laboratory, 15 ml of venous blood was collected from the antecubital vein of each participant.

For the analysis of total cholesterol, triglyceride (TG), high-density lipoprotein cholesterol (HDL-C), low-density lipoprotein cholesterol (LDL-C), and fasting blood glucose (FBG) levels, blood was collected into tubes containing clotting activators for serum isolation. The samples were allowed to clot for 45 min at room temperature and centrifuged at 3,000 rpm for 10 min at 4 °C. After centrifugation, serum was dispensed into plain microtubes and stored at −80 °C until analysis. These biomarkers were measured using enzymatic methods (Cobas c702, Roche Diagnostics, Basel, Switzerland).

Insulin levels were quantified using an electrochemiluminescence immunoassay (Elecsys Insulin Kit, Roche Diagnostics, Basel, Switzerland). The homeostasis model assessment of insulin resistance (HOMA-IR) was calculated according to the formula [fasting insulin [μU/ml] × fasting plasma glucose [mg/dl]/405], as proposed by Matthews et al. (41). HbA1c levels were determined using an automated glycohemoglobin analyzer (HLC-723G8, Tosoh Corporation, Tokyo, Japan), and GLP-1 levels were assessed using enzyme-linked immunosorbent assays (ELISA Kit, R&D Systems, Minneapolis, MN, USA).

## 2.6 Taekwondo training program

The Taekwondo training program was adapted and modified from the recommendations set forth by Jung et al. (28) and was based on the American College of Sports Medicine's (ACSM) frequency, intensity, type, and time recommendations for older individuals (42–44). Each session consisted of a 10-min warm-up, 40-min main exercise, and 10 min cool-down, conducted three times per week for 12 weeks. The primary exercise consisted of fundamental Taekwondo techniques and kicking maneuvers executed with Thera-Bands for resistance training. In the initial 4-week period, the participants engaged in the practice of fundamental movements. During the subsequent 8-week phase, they performed Taekwondo movements with a yellow Thera-Band. In the final 4-week period, they utilized a red Thera-Band, progressively elevating the intensity of exercises. In accordance with the ACSM (45), the intensity of the exercise was increased at 4-week intervals, and the Rating of Perceived Exertion (RPE) was evaluated according to Borg (46). To ensure participant safety and adherence, adjustments were made when necessary, including modifying the range of motion or reducing the number of repetitions based on individual conditions. All modifications were implemented under the supervision of exercise professionals. The specifics of the Taekwondo training program are outlined in Table 2.

## 2.7 Statistical analysis

All variables were analyzed using SPSS version 22.0 for Windows (IBM, Chicago, IL, USA). Descriptive statistics, including means and standard deviations, were calculated for all variables.

The homogeneity of baseline characteristics between the Taekwondo and control groups was assessed using either an independent *t*-test or the Mann–Whitney *U* test, depending on the data distribution. To evaluate between-group differences over time, a two-way repeated measures ANOVA was conducted. Spearman's rank correlation coefficient was employed to determine inter-variable relationships, and linear regression analysis was conducted to examine scatter plots. Statistical significance was set at $p < 0.05$.

# 3 Results

## 3.1 Thigh muscle cross-sectional area and body composition

As indicated in Table 3, the results of thigh muscle CSA and body composition are as follows. The Taekwondo group exhibited a significant reduction in body mass ($p < 0.05$), body mass index (BMI) ($p < 0.01$), percent body fat ($p < 0.05$), and MAP ($p < 0.05$) after 12 weeks. Conversely, there was a significant increase in thigh muscle CSA ($p < 0.01$), appendicular skeletal muscle mass (ASM) ($p < 0.05$). Furthermore, the interaction between-group and time was significant for thigh muscle CSA ($p = 0.013$), body mass ($p = 0.007$), BMI ($p < 0.001$), LBM ($p = 0.013$), percent body fat ($p = 0.010$), WHR ($p = 0.040$), LLM ($p = 0.025$), ASM ($p = 0.008$), and MAP ($p = 0.015$).

As shown in Figure 1, the Taekwondo group exhibited a significant reduction in body fat percentage compared to baseline ($p < 0.05$), whereas the control group showed no significant changes. Additionally, thigh muscle CSA significantly increased in the Taekwondo group ($p < 0.01$), while the control group

TABLE 2 Taekwondo training program.

| Item | Contents | | | Time (min) |
|---|---|---|---|---|
| Warm-up | Shuttle walking, sit down and stretch forward, lean forward with your legs open, ankle twist, raise one leg up and lean forward (both sides), put your feet together and lean forward, put your hands together and lean back, clasped up with both hands, clasped both hands and stretches to the side, lean forward with both hands clasped, push both arms against the wall | | | 10 |
| Exercises | 1–4 week | Seogi–Moaseogi, Naranhiseogi, Juchumseogi, Apseogi, Jireugi–Underneath, Trunk, Face opposite, Makgi–Naeryeomakgi, Anmakgi, Ollyeomakgi, Chagi(sitting)–Apchagi, Dollyeochagi, Naeryeochagi<br>*Repeat 10–12 times after memorizing each action | RPE: <10 | 40 |
| | 5–8 week | Seogi–Moaseogi, Naranhiseogi, Juchumseogi Jireugi–Underneath, Trunk, Face opposite, Side Makgi–Naeryeomakgi, Anmakgi, Ollyeomakgi Chagi(sitting)–Apchagi, Dollyeochagi, Naeryeochagi<br>*10 repetitions after memorizing each action (2set) | RPE: 10–11<br>Thera-Band Yellow | |
| | 9–12 week | Seogi–Apgubi, Dwitgubi, Beomseogi Jireugi–Underneath, Trunk, Face opposite, Side Makgi–Yeommakgi, Bakkanmakgi, Biteureomakgi Chagi(standing)-Apchagi, Dollyeochagi, Naeryeochagi<br>*10 repetitions after memorizing each action (3 set) | RPE: 12–13<br>Thera-Band Red | |
| Cool-down | Sit down and stretch forward, lean forward with your legs open, ankle twist, raise one leg up and lean forward (both sides), put your feet together and lean forward, put your hands together and lean back, clasped up with both hands, clasped both hands and stretches to the side, lean forward with both hands clasped, push both arms against the wall | | | 10 |

TABLE 3 Changes in thigh muscle cross-sectional area, body composition between groups at baseline and after 12 weeks.

| Variable | Group | Baseline | 12 weeks | % diff | *p*-value (interaction) |
|---|---|---|---|---|---|
| Thigh muscle CSA ($mm^2$) | Taekwondo | 8,913.44 ± 1,695.53 | 9,804.56 ± 1,331.31 | 10.00** | 0.013 |
| | Control | 8,367.56 ± 1,138.79 | 8,305.33 ± 968.63 | −1.32 | |
| Body mass (kg) | Taekwondo | 58.89 ± 6.68 | 57.54 ± 5.45 | −2.28* | 0.007 |
| | Control | 55.38 ± 4.29 | 55.80 ± 3.69 | 1.16 | |
| BMI ($kg/m^2$) | Taekwondo | 26.54 ± 2.94 | 25.66 ± 2.46 | −3.34** | <0.001 |
| | Control | 24.91 ± 2.25 | 25.14 ± 2.15 | 1.19 | |
| LBM (kg) | Taekwondo | 33.31 ± 3.57 | 34.71 ± 3.39 | 4.20* | 0.013 |
| | Control | 31.92 ± 2.89 | 32.36 ± 2.50 | 1.88 | |
| Percent body fat (%) | Taekwondo | 42.27 ± 4.13 | 40.80 ± 4.28 | −5.70* | 0.010 |
| | Control | 42.19 ± 5.25 | 42.41 ± 4.88 | 0.48 | |
| WHR | Taekwondo | 0.91 ± 0.04 | 0.89 ± 0.03 | −1.50 | 0.040 |
| | Control | 0.94 ± 0.03 | 0.95 ± 0.03 | 2.13 | |
| LLM (kg) | Taekwondo | 9.69 ± 1.12 | 9.88 ± 1.10 | 2.00 | 0.025 |
| | Control | 9.66 ± 1.09 | 9.41 ± 0.92 | −2.26 | |
| ASM (kg) | Taekwondo | 13.17 ± 1.53 | 13.65 ± 1.36 | 3.64* | 0.008 |
| | Control | 12.90 ± 1.34 | 12.61 ± 1.16 | −1.96 | |
| MAP (mmHg) | Taekwondo | 106.56 ± 13.81 | 98.59 ± 7.06 | −7.47* | 0.015 |
| | Control | 105.30 ± 10.94 | 106.41 ± 7.47 | 2.58 | |

Values are represented as mean ± standard deviation.

Significantly different from baseline: *$p < 0.05$, **$p < 0.01$.

Thigh muscle CSA, thigh muscle cross-sectional area; BMI, body mass index; LBM, lean body mass; WHR, waist-hip ratio; LLM, lower limb muscle mass; ASM, appendicular skeletal muscle mass; MAP, mean arterial pressure.

exhibited a non-significant decrease. Significant interaction effects were observed for both variables ($p < 0.05$).

## 3.2 Health-related physical fitness

HRPF and SPPB outcomes are presented in Table 4. In the Taekwondo group, significant post-intervention improvements were observed in the SLST ($p < 0.01$), maximal stride length ($p < 0.05$), and SPPB ($p < 0.05$). Additionally, the TUG test showed a significant reduction ($p < 0.01$).

Moreover, significant interaction effects between-group and time were identified for repeated chair stand ($p = 0.012$), SLST ($p = 0.003$), TUG test ($p = 0.011$), maximal gait speed ($p = 0.045$), maximal stride length ($p = 0.013$), and SPPB ($p = 0.010$).

As shown in Figure 2, the Taekwondo group exhibited a significant increase in SLST time compared to baseline ($p < 0.01$), whereas the control group showed no significant changes. Additionally, the SPPB score increased in the Taekwondo group, while the control group exhibited a slight decrease. Significant interaction effects were observed for SLST ($p < 0.01$) and SPPB ($p < 0.05$).

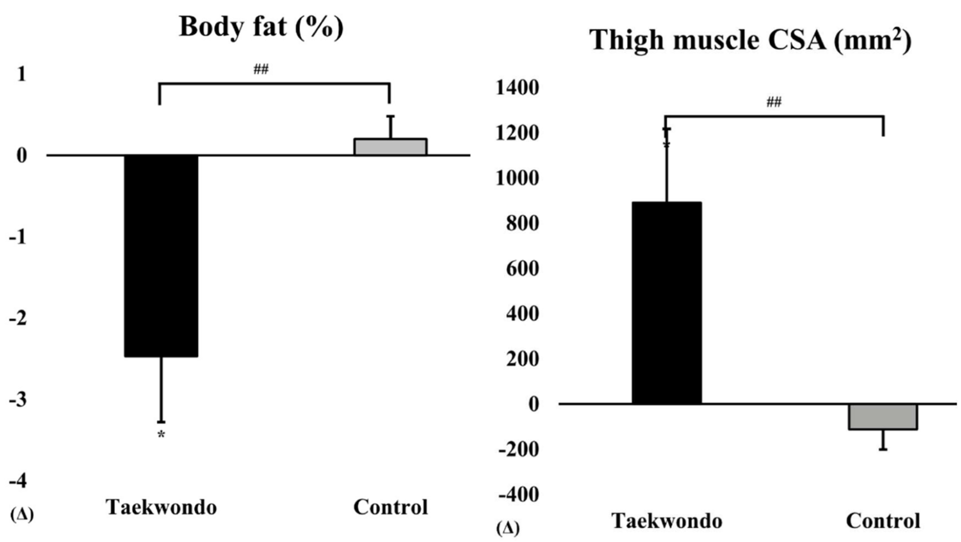


FIGURE 1
Comparison of body fat (%) and thigh muscle CSA between baseline and after 12 weeks in taekwondo program. #: $p$-value (interaction) ##$p < 0.01$. *: $p$-value (time) *$p < 0.05$. Δ: Post–Pre. Thigh muscle CSA, thigh muscle cross-sectional area.

TABLE 4 Changes in HRPF between groups at baseline and after 12 weeks.

| Variable | Group | Baseline | 12 weeks | % diff | $p$-value (interaction) |
|---|---|---|---|---|---|
| Hand grip strength (kg) (dominant) | Taekwondo | 21.29 ± 3.95 | 22.09 ± 3.58 | 3.76 | 0.566 |
| | Control | 21.36 ± 2.86 | 21.40 ± 2.94 | 0.03 | |
| Repeated chair stand (s) | Taekwondo | 8.76 ± 2.21 | 7.95 ± 1.84 | −9.34 | 0.012 |
| | Control | 8.77 ± 2.62 | 9.24 ± 2.51 | 6.20 | |
| 2-minute walking test (frequency) | Taekwondo | 103.67 ± 26.33 | 110.89 ± 21.08 | 6.97 | 0.085 |
| | Control | 101.22 ± 24.83 | 92.78 ± 31.28 | −8.51 | |
| SLST(s) (dominant) | Taekwondo | 4.02 ± 3.68 | 11.27 ± 6.40 | 180.35** | 0.003 |
| | Control | 3.44 ± 1.98 | 2.83 ± 2.14 | −16.88 | |
| TUG (s) | Taekwondo | 6.92 ± 0.65 | 6.33 ± 0.56 | −8.54** | 0.011 |
| | Control | 6.24 ± 0.71 | 6.61 ± 1.11 | 4.05 | |
| Normal gait speed (m/s) | Taekwondo | 1.01 ± 0.21 | 1.07 ± 0.17 | 5.21 | 0.403 |
| | Control | 0.99 ± 0.21 | 0.92 ± 0.11 | −4.48 | |
| Maximal gait speed (m/s) | Taekwondo | 0.69 ± 0.06 | 0.70 ± 0.03 | 1.53 | 0.045 |
| | Control | 0.67 ± 0.07 | 0.61 ± 0.08 | −9.47 | |
| Maximal stride length (cm) | Taekwondo | 78.78 ± 14.02 | 81.11 ± 12.98 | 2.96* | 0.013 |
| | Control | 78.89 ± 13.40 | 70.78 ± 15.00 | −6.92 | |
| SPPB (score) | Taekwondo | 10.22 ± 1.20 | 11.22 ± 1.56 | 9.78* | 0.010 |
| | Control | 9.89 ± 1.36 | 9.56 ± 1.33 | −3.75 | |

Values are represented as mean ± standard deviation.
Significantly different from baseline: *$p < 0.05$, **$p < 0.01$.
SLST, single-leg stance test; TUG, timed up and go; SPPB, short physical performance battery.

## 3.3 Laboratory markers

Changes in blood lipid levels and insulin resistance markers are presented in Table 5. In the Taekwondo group, significant reductions were observed in TG, FFA, FBG, insulin, HbA1c, and HOMA-IR whereas GLP-1 levels showed a significant increase. Moreover, significant interaction effects between-group and time were observed for TG ($p = 0.036$), HDL-C ($p = 0.031$), FFA ($p = 0.045$), FBG ($p = 0.009$), HbA1c ($p = 0.025$), and GLP-1 ($p < 0.001$) levels.

As shown in Figure 3, HbA1c levels tended to decrease in the Taekwondo group compared to baseline, whereas a slight increase was observed in the control group. A significant interaction effect was found between the two groups ($p < 0.05$). Additionally, GLP-1 levels significantly increased in the Taekwondo group compared to baseline ($p < 0.01$), whereas a decreasing trend was observed in the control group. A significant interaction effect was observed between the two groups ($p < 0.001$).

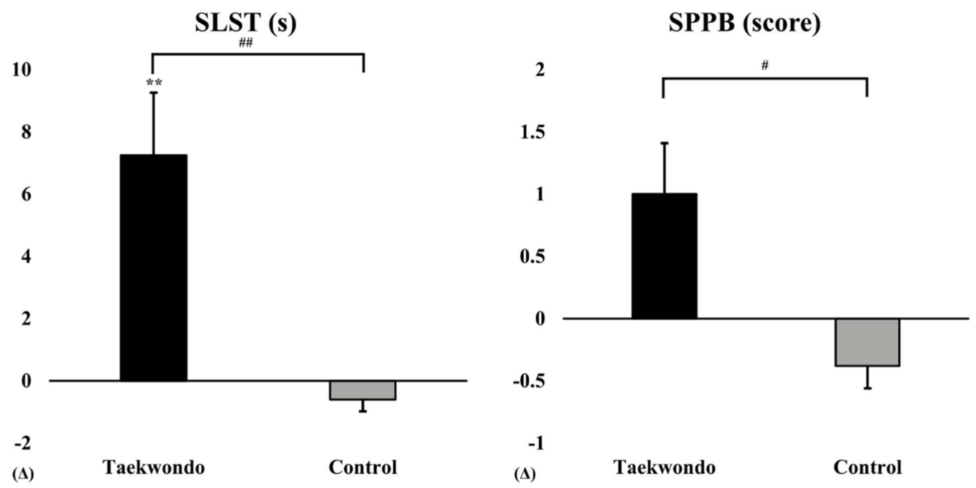


FIGURE 2
Comparison of SLST and SPPB between baseline and after 12 weeks in taekwondo program. #: $p$-value (interaction) #$p < 0.05$, ##$p < 0.01$. *: $p$-value (time) **$p < 0.01$. Δ: Post–Pre. SLST, single-leg stance test; SPPB, short physical performance battery.

TABLE 5 Changes in laboratory markers.

| Variable | Group | Baseline | 12 weeks | % diff | $p$-value (interaction) |
|---|---|---|---|---|---|
| TC (mg/dl) | Taekwondo | 173.67 ± 44.59 | 159.67 ± 13.16 | −8.06 | 0.226 |
| | Control | 165.13 ± 34.65 | 178.75 ± 30.01 | 8.25 | |
| TG (mg/dl) | Taekwondo | 126.00 ± 43.30 | 92.78 ± 23.95 | −26.37* | 0.036 |
| | Control | 132.56 ± 48.13 | 144.33 ± 43.68 | 9.55 | |
| HDL-C (mg/dl) | Taekwondo | 56.44 ± 12.02 | 64.44 ± 11.64 | 14.17 | 0.031 |
| | Control | 60.00 ± 19.03 | 51.00 ± 6.28 | −15.95 | |
| LDL-C (mg/dl) | Taekwondo | 106.44 ± 38.35 | 104.11 ± 13.51 | −2.19 | 0.227 |
| | Control | 90.00 ± 31.24 | 103.88 ± 32.87 | 15.42 | |
| FFA (µmol/L) | Taekwondo | 606.78 ± 340.26 | 498.56 ± 222.32 | −17.84* | 0.045 |
| | Control | 608.13 ± 237.90 | 726.38 ± 250.77 | 6.80 | |
| FBG (mg/dl) | Taekwondo | 120.56 ± 13.70 | 100.44 ± 12.89 | −16.68* | 0.009 |
| | Control | 117.44 ± 8.95 | 120.56 ± 6.73 | 2.65 | |
| Insulin (µU/ml) | Taekwondo | 19.59 ± 16.69 | 8.24 ± 3.84 | −57.91* | 0.058 |
| | Control | 11.44 ± 7.00 | 13.09 ± 6.40 | 14.77 | |
| HbA1c (%) | Taekwondo | 5.93 ± 0.47 | 5.71 ± 0.44 | −3.75* | 0.025 |
| | Control | 6.09 ± 0.69 | 6.20 ± 0.66 | 1.01 | |
| HOMA-IR | Taekwondo | 6.18 ± 6.27 | 2.07 ± 1.09 | −66.53* | 0.066 |
| | Control | 3.38 ± 2.20 | 3.95 ± 2.12 | 17.19 | |
| GLP-1 (ng/ml) | Taekwondo | 1.95 ± 0.50 | 2.80 ± 0.75 | 43.42** | <0.001 |
| | Control | 2.53 ± 1.66 | 1.78 ± 0.65 | −16.82 | |

Values are represented as mean ± standard deviation.
Significantly different from baseline: *$p < 0.05$, **$p < 0.01$.
TC, total cholesterol; TG, triglyceride; HDL-C, high-density lipoprotein cholesterol; LDL-C, low-density lipoprotein cholesterol; FFA, free fatty acid; FBG, fasting blood glucose; HbA1c, percentage of glycosylated hemoglobin A1c; HOMA-IR, homeostatic model assessment for insulin resistance; GLP-1, glucagon-like peptide 1.

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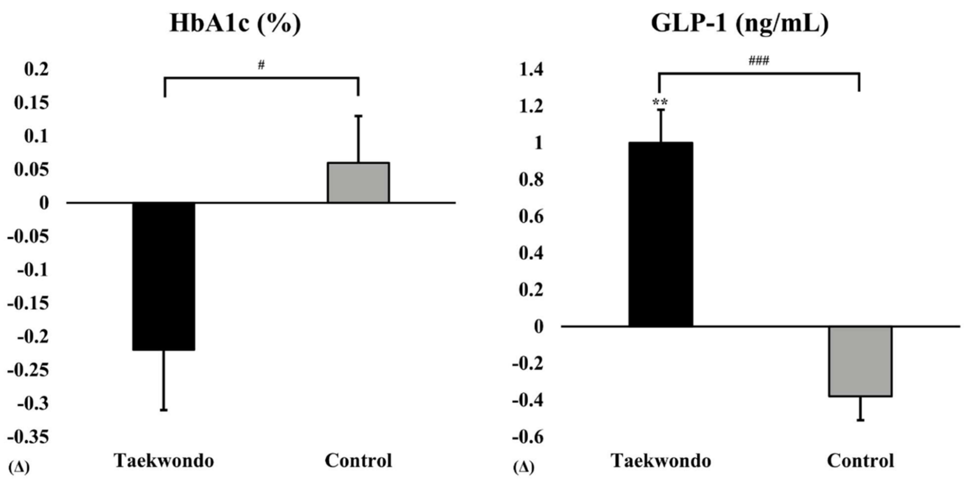


FIGURE 3
Comparison of HbA1c and GLP-1 between baseline and after 12 weeks in taekwondo program. #: $p$-value (interaction) #$p < 0.05$, ###$p < 0.001$. *: $p$-value (time) **$p < 0.01$. Δ: Post–Pre. HbA1c, percentage of glycosylated hemoglobin A1c; GLP-1, glucagon-like peptide 1.

TABLE 6 Correlation coefficient between changes in thigh muscle cross-sectional area and other variables.

| Variable | LBM (kg) | TUG (sec) | TG (mg/dl) | HDL-C (mg/dl) | FFA (µmol/L) |
|---|---|---|---|---|---|
| Thigh muscle cross-sectional area (mm$^2$) | 0.491* | −0.658** | −0.638** | 0.736** | −0.506* |
| | FBG (pg/ml) | Insulin (µU/ml) | HOMA-IR | GLP-1 (ng/ml) | |
| | −0.535* | −0.615** | −0.608** | 0.718** | |

LBM, lean body mass; TUG, timed up-and-go test; TG, triglyceride; HDL-C, high-density lipoprotein cholesterol; FFA, free fatty acid; FBG, fasting blood glucose; HOMA-IR, homeostatic model assessment for insulin resistance; GLP-1, glucagon-like peptide-1.
*$p < 0.05$.
**$p < 0.01$.

## 3.4 Correlation between thigh muscle cross-sectional area and other variables

The thigh muscle CSA demonstrated significant negative correlations with TUG ($r = -0.658$, $p < 0.01$), TG ($r = -0.638$, $p < 0.01$), FFA ($r = -0.506$, $p < 0.05$), FBG ($r = -0.535$, $p < 0.05$), insulin ($r = -0.615$, $p < 0.01$), and HOMA-IR ($r = -0.608$, $p < 0.01$) (Table 6). In contrast, significant positive correlations were observed for LBM ($r = 0.491$, $p < 0.05$), HDL-C ($r = 0.736$, $p < 0.01$), and GLP-1 ($r = 0.718$, $p < 0.01$).

# 4 Discussion

This study demonstrated that regular, long-term Taekwondo training significantly increased thigh muscle CSA in sedentary older women, an outcome of particular importance given the difficulty in improving muscle mass in this population. Increased thigh muscle CSA is associated with functional mobility, balance, and insulin sensitivity, thereby reducing fall risk and improving metabolic health, especially in older women with a sedentary lifestyle (22).

The significant improvements in thigh muscle CSA observed in this study may be due to the combined aerobic and resistance components of Taekwondo, particularly the dynamic kicking movements and postural changes that stimulate muscle growth (27, 47, 48). These movements effectively engage lower body muscles, promoting hypertrophy and strength in older adults. This is noteworthy as increasing muscle mass is challenging in older women due to age-related declines in muscle synthesis (49–53). However, Taekwondo's unique combination of dynamic resistance and functional movements appears particularly effective for stimulating muscle growth and improving insulin sensitivity in sedentary older women, highlighting its potential as a practical intervention for enhancing muscle mass and metabolic health in this population.

Increased thigh muscle CSA observed a positive association with the HRPF of sedentary older women. More specifically, the significant decline in the TUG test and the significant increase in single-leg stance test, maximum stride length in Taekwondo group indicate that Taekwondo training had a beneficial effects on balance and mobility in older individuals. These improvements are directly linked to the increases in thigh muscle CSA, highlighting the interconnectedness of muscle mass and physical function. The importance of regular exercise in sedentary older women are reducing the risk of falls, improving gait ability, and promoting independence in the older population (25, 54, 55). Our results indicate that the Taekwondo program has the potential to enhance HRPF, particularly balance and gait, thereby reducing fall risk and increasing mobility.

Additionally, significant reductions in HbA1c and increases in GLP-1 levels were observed, suggesting enhanced glucose metabolism. Given the role of GLP-1 in promoting insulin secretion and improving insulin resistance, the observed increase in GLP-1 provides a plausible mechanism for the improvements in HbA1c and insulin sensitivity (56). This highlights the potential of Taekwondo as a multifaceted intervention that not only enhances muscle mass and physical fitness but also positively impacts metabolic health.

These findings underscore the importance of incorporating Taekwondo training as a strategic intervention for enhancing thigh muscle CSA, improving HRPF, and promoting metabolic health in sedentary older women. However, several limitations should be considered. The study's small sample size and the lack of a follow-up limit the generalizability of the results. Future studies should include larger, more diverse populations and consider longitudinal designs to assess the sustainability of the observed benefits. Furthermore, exploring the molecular mechanisms underlying the improvements in muscle mass and metabolic health will provide deeper insights into the efficacy of Taekwondo as an intervention for older adults.

## 5 Conclusion

Regular, long-term Taekwondo training has been demonstrated to enhance HRPF, total muscle mass, and thigh muscle CSA in sedentary older women, thereby contributing to improved insulin resistance risk factors. These findings suggest that Taekwondo training may be an effective exercise program to promote metabolic health in this population.

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Ethics statement

The studies involving humans were approved by This study was conducted in accordance with the guidelines set forth by the institutional review board of D University (IRB No. 2-1040709-AB-N-01-201904-HR-022-04). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

## Author contributions

JP: Conceptualization, Data curation, Investigation, Methodology, Project administration, Resources, Writing – original draft, Writing – review & editing. BK: Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Validation, Visualization, Writing – review & editing. MJ: Data curation, Investigation, Software, Writing – review & editing. H-HJ: Data curation, Investigation, Software, Writing – review & editing. GH: Conceptualization, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing – review & editing. SP: Conceptualization, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing – review & editing.

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## Conflict of interest

The 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.

## Generative AI statement

The author(s) declare that Generative AI was used in the creation of this manuscript. Generative AI was employed to refine sentence structure, enhance clarity, and translate content from Korean to English during the manuscript preparation process. The authors ensured all AI-assisted outputs were carefully reviewed and revised to maintain scientific accuracy and originality.

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# Weight cycling and relative energy deficiency in sport syndrome in an elite female muaythai athlete: a case study

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**Introduction:** Weight cycling—defined as repeated, chronic, and often extreme weight loss is a widespread practice in combat sports. However, it may lead to symptoms related to Relative Energy Deficiency in Sport (REDs). This case study investigates the impact of a five-week fight camp on the health and performance of an elite female Muaythai athlete, with a particular focus on metabolic and physiological adaptations.

**Methods:** A 23-year-old professional Muaythai fighter was monitored over a seven-week period, encompassing a control phase, a five-week fight camp, the fight week, and post-fight recovery. Measurements included body composition, resting metabolic rate (RMR), blood biomarkers, and performance in a cycling power test. Dietary intake and training load were also tracked.

**Results:** The athlete's RMR decreased by 253 kilocalories per day. Blood markers indicated increased creatinine and urea levels, along with unfavorable changes in lipid profile. Maximum cycling power output decreased by 27%. Despite a significant energy deficit, fat-free mass loss was limited to 0.6. These findings suggest metabolic adaptations, signs of renal strain, and symptoms of REDs.

**Conclusion:** Weight cycling induced physiological and metabolic adaptations consistent with REDs, negatively affecting health and performance. The results highlight the importance for individualized and evidence-based weight management strategies to mitigate negative health outcomes and enhance athletic performance in combat sports.

KEYWORDS
weight loss, athlete, female, body composition, health outcomes, combat sports

## 1 Introduction

In many combat sports, including boxing, judo, and Muaythai, athletes are categorized into weight classes, aligning competitors based on their weight to minimize the risk of injuries resulting from a significant weight advantage (1). The primary motivation behind manipulating body weight in these sports is to meet the weight limit of a specific weight class. It is common for athletes to compete in a weight class below their usual training body weight, employing both chronic weight loss (CWL) and rapid weight loss (RWL) strategies (1).

CWL involves sustaining an energy deficit over time, with the duration instated by the required weight loss (2). During the fight week (FW), athletes implement RWL strategies, that can result in body weight reduction up to 10%. These methods include fluid intake restriction, sodium reduction, glycogen store depletion, low-residue diets, and active and passive sweating. The extent of CWL and RWL implementation often depends on the interval between official weigh-ins and competition, which varies across amateur and professional settings (3–6).

Health risks associated with RWL include increased cortisol levels, hyponatremia, impaired immune function, and elevated creatinine levels, indicating acute kidney injury (7). Dehydration during RWL is linked to reduced plasma volume, increased blood viscosity, and heightened cardiovascular strain, raising the risk of cardiovascular problems. Moreover, RWL can negatively affect the mental health, leading to short-term declines in memory, concentration, self-esteem and an increase in confusion, depression, and aggression (4, 8, 9). The frequency of RWL strategy use is also associated with a higher incidence of injuries among fighters (10).

Despite known health risks and potential performance impairments, many athletes perceive the competitive advantage gained through weight cutting to outweigh the drawbacks (11). Evidence shows that RWL can impair performance, particularly when recovery time post-weigh-in is less than one hour (12). However, research by Mendes (13) and Cengiz (14) suggests that adequate recovery time can help mitigate these adverse effects.

On the other hand, CWL is linked with the risk of developing Relative Energy Deficiency in Sport syndrome (REDs) (15). REDs reflect adverse physiological effects observed in athletes when their energy intake does not adequately cover the body's functional needs after subtracting training or competition energy expenditure. Its effects include menstrual, endocrine, metabolic (e.g., reduced resting metabolic rate), hematological (e.g., elevated creatinine and urea), psychological, cardiovascular, gastrointestinal, and immunological disturbances (16). These consequences impair training adaptations and performance by reducing endurance capacity, increasing injury risk, lowering training adherence, impairing coordination, depleting glycogen stores, suppressing muscle protein synthesis, and reducing muscle strength (16). Case studies by Kasper (7) and Langan-Evans (17) provide vivid examples of REDs during fight preparation.

Over the past two decades, considerable research has explored the physiological and psychological consequences of weight manipulation in combat sports. Studies across nutrition, exercise physiology, and sports psychology have documented the prevalence, methods, and effects of weight-cutting strategies, establishing a solid knowledge base (18, 19). Seminal contributions—such as those by Franchini (11) and Artioli (12), have detailed the widespread use of RWL and its negative consequences on athlete health and performance. However, prior research has largely overlooked how these practices affect specific athlete profiles, especially in underrepresented populations such as female fighters (19). The current study addresses this gap by contextualizing weight-cutting strategies within the complex training framework of an elite female athlete.

In recent years, there has been growing recognition of the health and performance risks linked to body weight manipulation in combat sports (7, 17). This case study adds to current knowledge by examining a female Muaythai athlete and how weight-cutting strategies affect her health and performance.We hypothesize that combining chronic weight loss (CWL) and rapid weight loss (RWL) has a negative impact on female athletes. RWL may increase the risk of acute complications such as dehydration, cardiovascular strain, and cognitive issues (7, 17), while CWL may lead to longer-term problems, including REDs (16, 17). These effects likely depend on the time available for recovery between weigh-in and competition.

This study aims to explore how CWL and RWL strategies contribute to the development of REDs through monitoring physiological, metabolic, and performance changes during a structured fight camp in a female Muaythai athlete.

# 2 Materials and methods

## 2.1 Athlete overview

The subject was a 23-year-old professional female Muaythai athlete (57.5 kg, 1.65 m) diagnosed with hypothalamic secondary amenorrhea. Since starting her competitive career at 18, she has participated in 48 bouts (22–13 amateur, 8–5 professional). Based on the McKay et al. classification (20), she qualifies as a Tier 4 athlete. She typically competes 8–10 times per year in the flyweight (>51 kg) and bantamweight (>54 kg) categories, following consistent weight-loss patterns. Prior to the study, she had been training six times weekly for three months (4 Muaythai sessions, 2 strength training sessions).

## 2.2 Case report design and overview of nutritional and training intervention

The athlete underwent a simulated fight preparation to reduce body mass for the bantamweight category (<54 kg), requiring a > 3.5 kg (>6%) weight loss over five weeks. The preparation for the simulated fight mirrored that of a real fight, with the female athlete participating in a fight camp aimed at reducing her body weight. The follow-up period included one control week and one post-match week for a total follow-up period of 7 weeks.

Instead of an actual bout, a critical performance test was used as a simulated fight (SF), occurring four hours post weigh-in (WI) under amateur conditions. The objective was to closely approximate the natural conditions of a real fight, with the female athlete undergoing a critical power test at a time corresponding to when a real fight would occur. The total observation period was 7 weeks, divided into four phases of varying durations of several weeks (WK) or days (D).

**Phase 1:** Control week (CW) 7D—general training regime when the fighter is not in preparation for a fight.

**Phase 2:** Fight camp diet (FCD) 28D (−5WK, −4WK, −3WK, −2WK)—training regime focused on weight reduction and specific skills for a fight.

**Phase 3:** Fight week (FW) 4D (−1WK, WI + SF)- final weight loss using RWL strategies and reduced training load and weigh-in + simulated fight.

**Phase 4:** Post-fight week (PFW) – 7D (+1WK) – a more relaxed eating and training regime).

The methodology further elaborates on the measurements used.

**Phase 1:** During Phase 1 CW, the female athlete followed a diet *ad libitum*. The average daily energy intake was 2 198 ± 128kcal (Table 1). Macronutrient breakdown included 72 ± 10 g of fat (1.3 g/kg/d), 285 ± 33 g of carbohydrates (5 g/kg/d), and 104 ± 6g of protein (1.8 g/kg/d) during this phase. Fiber intake in Phase 1 was 26 ± 5 g/d. The female athlete's weekly training schedule (refer to Table 2) included one aerobic continuous bike ride (BR), two resistance training sessions (RT), three Muaythai training sessions (MT), and one other training session (OT). The aerobic BR involved a 60-min bicycle ride at a cycling speed corresponding to FATpeak. RT comprised a whole-body workout with general strength/speed exercises concurrently performed in a superset, incorporating speed/strength, ballistic, and reactive strength modalities. Volume loads and intensities were determined through 1 repetition maximum (RM) testing. MT training was specific sports training lasting 60–90 min, and OT involved sports activity at college (the athlete is a student).

**Phase 2:** The female athlete followed a fight camp diet based on the "3,2,1" principle, entailing macronutrient intake of 3 g/kg/d for carbohydrates, 2 g/kg/d for proteins, and 1 g/kg/d for fats (2, 21). This dietary approach is a standard practice for the athlete in preparation for a fight. The energy intake during this phase averaged 1,525 ± 29 kcal per day (Table 1). Macronutrient distribution included 50 ± 2 g of fat (0.8 g/kg/d), 170 ± 4 g of carbohydrates (3 g/kg/d), and 104 ± 3 g of protein (1.8 g/kg/d). In Phase 2, the fiber intake was 21 ± 2 g. A detailed description of −5 WK to −2 WK is provided in Table 1. The athlete's weekly training schedule (Table 2) comprised one aerobic continuous bike ride (BR), two resistance training sessions (RT), three Muaythai training sessions (MT), one Interval training (IT), one psychomotor training (PT), and one other training session (OT). PT involved exercises with a tennis ball (juggling, catching the ball in punches, etc.) for 30 min. IT on the assault bike included a 5–10-minute warm-up, followed by 6 × 5 min at 90% HR max (rest between intervals 2 min), and a 5-minute cool down (total training time 50–60 min).

**Phase 3:** In the fight week, the female athlete incorporated rapid weight loss (RWL) strategies such as glycogen store depletion, low fiber intake, and low sodium intake over a 4-day duration (−1 WK). The energy intake averaged 1 371 ± 65kcal per day (Table 1). Macronutrient breakdown included 92 ± 5 g of fat (1.6 g/kg/d), 62 ± 10 g of carbohydrates (1.1 g/kg/d), and 85 ± 10 g of protein (1.5 g/kg/d). In Phase 3, the fiber intake was 7 ± g. A detailed description of −1 WK is outlined in Table 3. The athlete's weekly training schedule (Table 2) included three Muayhai training sessions.

After the weigh-in (4-hour period), the energy intake was 1,013 kcal. Macronutrients consisted of 12 g of fat (0.2 g/kg), 205 g of carbohydrates (3.8 g/kg), and 15 g of protein (0.3 g/kg), with a fiber intake of 2 g. Fluid intake was 2.2 liters, and sodium intake was 2.24 g.

**Phase 4:** In the post-fight week, the female athlete consumed food and fluids *ad libitum*. The energy intake averaged 2 093 ± 106 kcal per day (Table 1). Macronutrient distribution

TABLE 1 Energy intake, expenditure, and availability across all study phases (mean ± SD).

| Phase | EI (kcal/day) | DIT (kcal/day) | NEAT (kcal/day) | EEE (kcal/day) | 24-h EB (kcal/day) | EA (kcal/kg FFM/day) |
|---|---|---|---|---|---|---|
| Control week | 2,198 ± 138 | 220 ± 14 | n/a | 304 ± 317 | n/a | 42 ± 6 |
| −5 WK | 1,541 ± 30 | 154 ± 3 | 238.0 ± 96.0 | 393 ± 279 | −792.0 ± 404.0 | 25 ± 6 |
| −4 WK | 1,557 ± 39 | 156 ± 4 | 303.0 ± 67.0 | 381 ± 240 | −712.0 ± 262.0 | 26 ± 5 |
| −3 WK | 1,496 ± 43 | 149 ± 4 | 249.0 ± 104.0 | 387 ± 244 | −945.0 ± 246.0 | 25 ± 6 |
| −2 WK | 1,506 ± 34 | 151 ± 3 | 241.0 ± 23.0 | 353 ± 241 | −845.0 ± 253.0 | 26 ± 6 |
| −1 WK | 1,371 ± 65 | 137 ± 7 | 298.0 ± 50.0 | 380 ± 36 | −1,034.0 ± 161.0 | 22 ± 1 |
| +1 WK | 2,096 ± 107 | 210 ± 11 | n/a | 354 ± 51 | n/a | 41 ± 3 |

EI, energy intake; DIT, diet-induced thermogenesis; NEAT, non-exercise activity thermogenesis; EEE, exercise energy expenditure; 24-h EB, 24-hour energy balance; EA, energy availability (per kg of fat-free mass); WK, week.
Values for Control Week and +1 WK may not include NEAT and EB due to technical limitations in data collection.

TABLE 2 Training schedule.

| Type of training | Phase 1 | Phase 2 | | | | Phase 3 | | Phase 4 |
|---|---|---|---|---|---|---|---|---|
| | .−6 WK | .−5 WK | .−4 WK | .−3 WK | .−2 WK | .−1 WK | WI + F | . +1 WK |
| Muaythai | 3 | 3 | 4 | 4 | 4 | 3 | 1 | 4 |
| Strenght | 2 | 2 | 3 | 3 | 2 | | | |
| Psychomotoric | | 1 | 1 | 2 | 2 | | | |
| Intervals | | 1 | 1 | 1 | | | | |
| Aerobic | 1 | 1 | | 1 | 1 | | | |
| Other | 1 | 1 | | | | | | 1 |
| Total | 7 | 9 | 9 | 11 | 9 | 4 | | 5 |

WK, week; WI, weigh-in, F, fight. Phase 1 – control week, Phase 2 - fight camp diet, Phase 3 - fight week and Phase 4 - post-fight week.

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TABLE 3 Within-day energy balance calculation.

| Date | | Intake | Expenditure | | | | Hourly calculations | EB hr by hr |
|---|---|---|---|---|---|---|---|---|
| | Time | EI | DIT | NEAT | EEE | BMR | TEE hr to hr | |
| 24.05.2021 | 0:00–1:00 | 0 | 0 | 0 | 0 | 64 | 64 | −64 |
| | 1:00–2:00 | 0 | 0 | 0 | 0 | 64 | 64 | −64 |
| | 2:00–3:00 | 0 | 0 | 0 | 0 | 64 | 64 | −64 |
| | 3:00–4:00 | 0 | 0 | 0 | 0 | 64 | 64 | −64 |
| | 4:00–5:00 | 0 | 0 | 0 | 0 | 64 | 64 | −64 |
| | 5:00–6:00 | 0 | 0 | 0 | 0 | 64 | 64 | −64 |
| | 6:00–7:00 | 0 | 0 | 0 | 0 | 64 | 64 | −64 |
| | 7:00–8:00 | 0 | 0 | 11 | 0 | 64 | 74 | −64 |
| | 8:00–9:00 | 0 | 0 | 33 | 0 | 64 | 97 | −64 |
| | 9:00–10:00 | 261 | 26 | 11 | 0 | 64 | 100 | 161 |
| | 10:00–11:00 | 0 | 0 | 35 | 0 | 64 | 99 | −99 |
| | 11:00–12:00 | 405 | 41 | 55 | 0 | 64 | 160 | 245 |
| | 12:00–13:00 | 0 | 0 | 31 | 0 | 64 | 94 | −94 |
| | 13:00–14:00 | 0 | 0 | 2 | 300 | 64 | 366 | −366 |
| | 14:00–15:00 | 0 | 0 | 45 | 0 | 64 | 108 | −108 |
| | 15:00–16:00 | 300 | 30 | 23 | 0 | 64 | 117 | −117 |
| | 16:00–17:00 | 0 | 0 | 9 | 0 | 64 | 73 | −73 |
| | 17:00–18:00 | 0 | 0 | 24 | 0 | 64 | 88 | −88 |
| | 18:00–19:00 | 0 | 0 | 0 | 590 | 64 | 654 | −654 |
| | 19:00–20:00 | 561 | 56 | 27 | 0 | 64 | 146 | 415 |
| | 20:00–21:00 | 21 | 2 | 1 | 0 | 64 | 67 | −65 |
| | 21:00–22:00 | 0 | 0 | 0 | 0 | 64 | 64 | −64 |
| | 22:00–23:00 | 0 | 0 | 0 | 0 | 64 | 64 | −64 |
| | 23:00–24:00 | 0 | 0 | 0 | 0 | 64 | 64 | −64 |
| | 24-h Total | 1,548 | 155 | 307 | 890 | 1,530 | 2,882 | −1,609 |

EI, energy intake; DIT, diet-induced thermogenesis; NEAT, non-exercise activity; EEE, energy exercise expenditure; BMR, basal metabolic rate; TEE, total energy expenditure; and EB, energy balance, Phase 1 – control week, Phase 2 - fight camp diet, Phase 3 - fight week and Phase 4 - post-fight week.

included 70 ± 11 g of fat (1.2 g/kg/d), 263 ± 22 g of carbohydrates (4.7 g/kg/d), and 107 ± 12 g of protein (1.8 g/kg/d). In Phase 4, the fiber intake was 20 ± 4 g. The athlete's weekly training schedule (Table 2) included four Muaythai training sessions (MT) and one other training session (OT).

Throughout all phases, no dietary supplements (except habitual coffee consumption) were implemented or allowed to limit potential ergogenic effects on subsequent performance-based testing.

## 2.3 Athlete assessment, assessment of training load, energy availability, within-day energy balance and weekly accumulated energy deficit

The athlete underwent a comprehensive assessment protocol across all phases of the study. All measurements and sampling were conducted in the fasted state, with the exception of a small carbohydrate-containing snack consumed 20 min before the critical power test. To improve clarity and allow effective tracking of physiological changes, assessed variables were categorized into four key domains:

- Morphological assessment:

Body mass (BM), body fat percentage (BF%), fat-free mass (FFM), and fat mass (FM), assessed using dual-energy x-ray absorptiometry (DXA; QDR Series Horizon, Hologic Inc.) and bioelectrical impedance analysis (InBody 770). DXA values were also used to calculate energy availability (EA).

- Functional performance assessment:

Maximal, average, and minimal power output during a 4-minute cycling test (Lode Excalibur Sport), along with derived indices such as relative power, fatigue rate, and total work, used to evaluate anaerobic performance and neuromuscular fatigue.

- Physiological and metabolic profiling:

Resting metabolic rate (RMR) was assessed via indirect calorimetry (Cortex Metalyzer 3B-R3), RMR prediction ($RMR_{pred}$), following Compher et al. (22), and was calculated using the Cunningham equation (23). A broad panel of blood biomarkers was analysed (24, 25). These included renal markers (creatinine, urea), plasma osmolality, glucose, insulin, thyroid hormones (TSH, fT3, fT4), IGF-1, lipid profile (total cholesterol, LDL, HDL, triglycerides), iron metabolism indicators (ferritin, transferrin, soluble transferrin receptor), bone turnover markers (vitamin D, Beta-cross laps, P1NP), inflammatory marker (C-reactive protein, CRP), and sex hormones (FSH, LH, estradiol, prolactin, SHBG, testosterone). Blood samples were collected via venipuncture and analysed in a certified laboratory using standardized procedures.

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- Nutritional and energy availability domain:

Daily dietary intake was recorded by the athlete over 46 days, covering all phases of the study: Phase 1 (7 days), Phase 2 (28 days), Phase 3 (4 days), and Phase 4 (7 days). Records were tracked via a mobile nutrition app under supervision and analyzed using NutriPro software. Energy intake (EI), diet-induced thermogenesis (DIT), exercise energy expenditure (EEE), non-exercise activity thermogenesis (NEAT), and within-day energy balance (24-h EB) were calculated for each phase. Energy availability (EA) was determined relative to fat-free mass based on DXA-derived values. Physical activity and training load data were collected using wearable devices (ActiGraph wGT3X-BT, Garmin HRM-Run 2).

A summary of the measurements for each phase is illustrated in Figure 1.

## 2.4 Ethical considerations

This study was approved by the Masaryk University Research Ethics Committee (EKV-2021-004). The participant provided written informed consent prior to data collection.

# 3 Results

## 3.1 Changes in anthropometric measurements

Figures 2–4 illustrate the temporal alterations in body mass (BM), fat mass (FM), fat-free mass (FFM), and body fat percentage (BF%). The athlete achieved the designated limit for

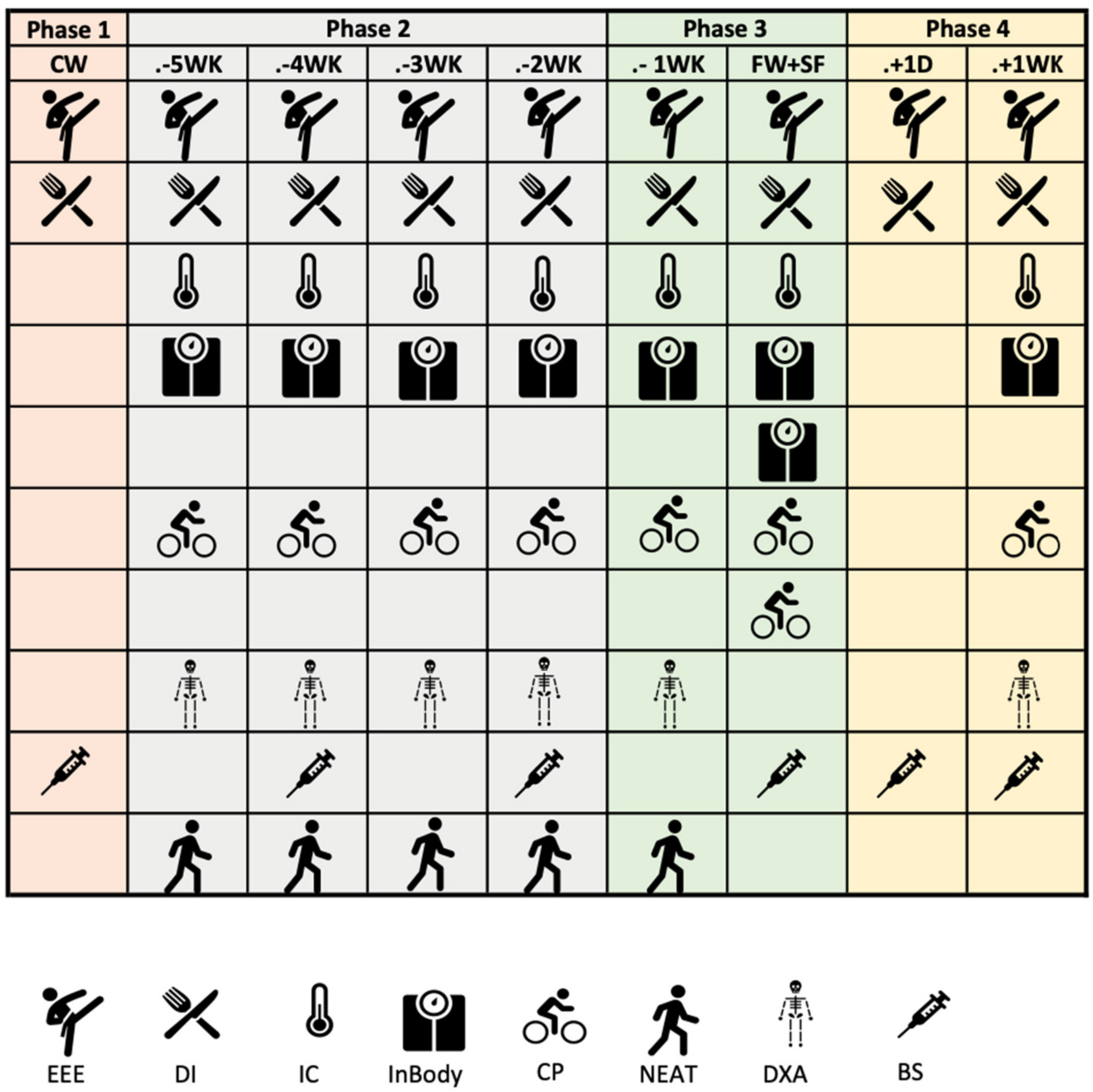


FIGURE 1
Instruments and parameters measured during the intervention. EEE, exercise energy expenditure; DI, dietary intake; IC, indirect calorimetry; CP, critical power test; NEAT, non-exercise energy expenditure; DXA - by dual-energy x-ray absorptiometry and BS, blood samples.

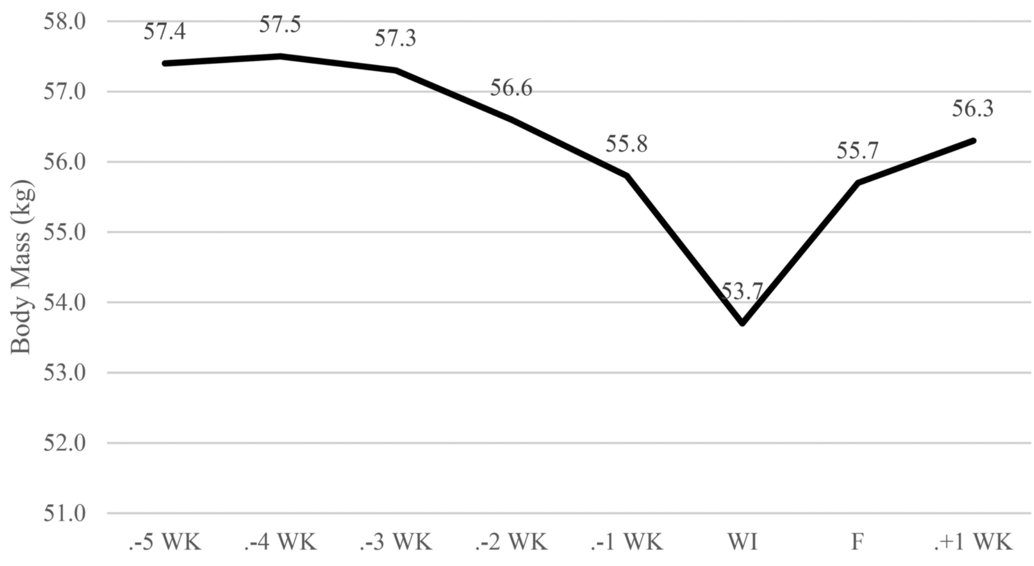


FIGURE 2
Changes in body mass. WK, week; WI, weigh-in, and F, fight. Phase 1 – control week, Phase 2 - fight camp diet, Phase 3 - fight week and Phase 4 - post-fight week.

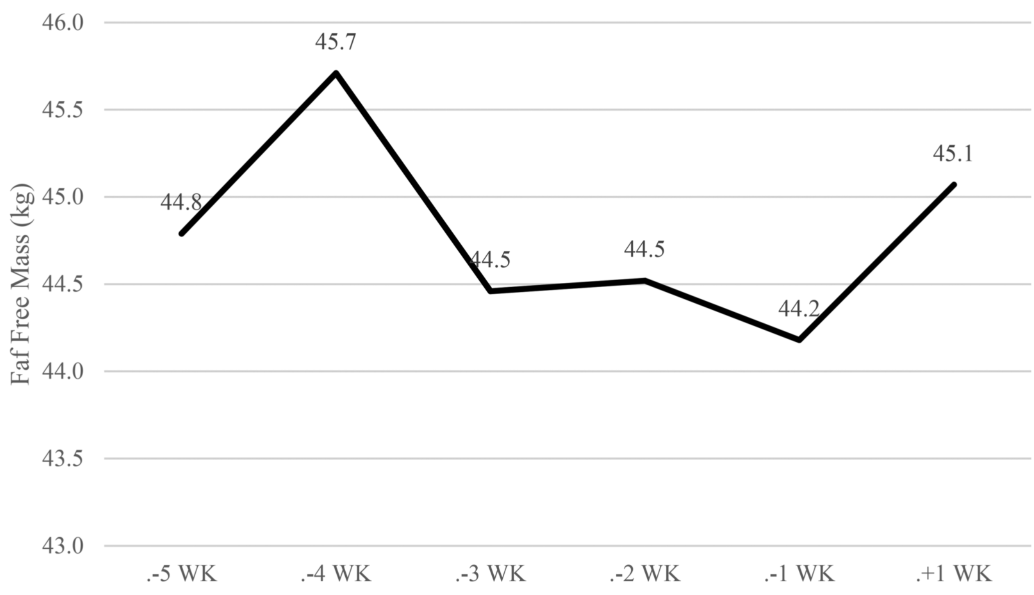


FIGURE 3
Changes in fat-free mass. WK, week; WI, weigh-in, and F, fight. Phase 1 – control week, Phase 2 - fight camp diet, Phase 3 - fight week and Phase 4 - post-fight week.

the selected bantamweight weight category for the simulation fight, recording an official weight of 53.7 kg at 9:00 AM.

Overall, there was a −3.7 kg (<6.4%) reduction in body weight, as depicted in Figure 2. This reduction comprised −0.6 kg (<1%) in FFM (Figure 3) and 1.8 kg (<3.1%) in FM (Figure 4) during Phase 2. Despite a body mass loss of 1.6 kg during Phase 2, the athlete still needed to shed an additional 1.8 kg in the subsequent 4 days.

In Phase 3 (fight week), body weight was further reduced by −2.1 kg (<3.8%) over 4 days. A 4-hour time delay between the weigh-in and the simulation fight (01:00 PM) allowed the athlete to regain 2 kg (>3.6%).

During the post-competitive recovery period in Phase 4, the athlete experienced an increase in BM by 2.6 kg (>4.8%), FM decreased by −0.5 kg (<0.9%), and FFM increased by 0.9 kg (>1.72%).

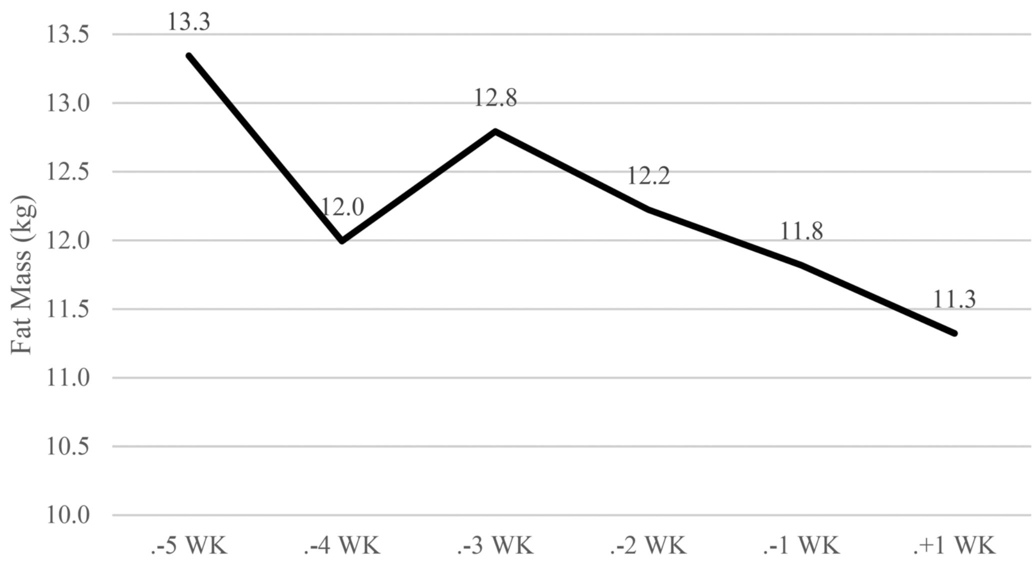


FIGURE 4
Changes in fat mass. WK, week; WI, weigh-in, and F, fight. Phase 1 – control week, Phase 2 - fight camp diet, Phase 3 - fight week and Phase 4 - post-fight week.

## 3.2 Assessment of low EA on markers of female athlete triad and REDs

At baseline, the athlete exhibited one established symptom of the Female Athlete Triad and REDs -hypothalamic amenorrhea. Therefore, the menstrual cycle phase did not influence the data. The assessment of the athlete's RMR is presented in Figure 5. In Phase 2, there was a reduction in RMR measured (RMRm) values by −93 kcal·d−1 at −4 WK, followed by an increase of +219 kcal·d−1 at −3 WK, a reduction of −49 kcal·d−1 at −2 WK, and −117 kcal·d−1 at −1 WK. Throughout Phases 3 and 4, there was a gradual reduction in RMRm values by −4 kcal·d−1 at -WI and −83 kcal·d−1 at +1 WK, resulting in an overall reduction from baseline of −127 kcal·d−1. Concerning RMRratio [RMRm vs. RMRpredicted—calculated by Cunningham (23)], values increased compared to RMRratio, with only −4 WK (0.97) and +1 WK (0.96) measurements showing a decrease compared to RMRratio. The reduction in RMRm in Phase 4 may result from dietary intervention during Phases 2 and 3, especially in Phase 3, where the average EA was 22 kcal·kg FFM-1 ·d-1.

Table 4 displays parameters observed during the 4-minute critical power test. Unfortunately, measurements from the beginning of Phase 2 are unavailable. For the −5 WK measurements, the bicycle ergometer VO2max test was initially chosen but was later replaced by the −4 WK critical power test, more specific to the athlete's sport. The critical power test (−4 WK) initially lasted 3 min, and due to an unclear indication of typical stress test fatigue, it was extended to 4 min. The athlete experienced a decrease in maximal power output throughout the observation period, with the highest value recorded at −3 WK (392 W). It is presumed that the values measured during the −5 WK and −4 WK periods would have been even higher. There was a decrease in maximum power, with the lowest values measured in Phase 3 (285 W). The highest level of fatigue was observed in Phase 3 WI (70.12), when the athlete was dehydrated and had reduced glycogen stores after using RWL strategies.

Table 5 details changes in biochemical parameters, with values outside reference limits highlighted in bold. Urea levels increased in the −2 WK and WI + SF periods, while creatinine levels increased in the −4 WK, −2 WK, WI + SF, and +1 D periods. Plasma osmolality was elevated (296 nmol/kg) during the V + Z period when the athlete was dehydrated due to Rapid Weight Loss (RWL) strategies. Insulin levels were within normal limits, except in the +1 D period when insulin levels were 2.5 mmol/L (indicating hypoglycemia). Total cholesterol and LDL values were elevated compared to reference values at the study's beginning and increased during the study, reaching their highest levels in the WI + SF period. Thyroid hormone levels gradually decreased, with the lowest TSH (3.681 ->2.075 mU/L) and fT3 (3.7 ->2.7 pmol/L) values in the WI + SF period, and fT4 (10.1 ->9.3 pmol/L) in the +1 D period. Vit. D values were suboptimal initially. Elevated Beta-cross laps and P1NP values at the study's beginning indicated increased bone turnover, possibly linked to the training intervention.

# 4 Discussion

This case study aimed to investigate the impact of the fight camp diet on health and performance parameters associated with REDs. Throughout the five weeks of low EA during the fight camp (mean daily value during Phase 2: 25.4 kcal·kg FFM-1 ·d-1 and Phase 3: 22.4 kcal·kg FFM-1 ·d-1), weight loss coincided with manifestations of REDs. Health consequences included a

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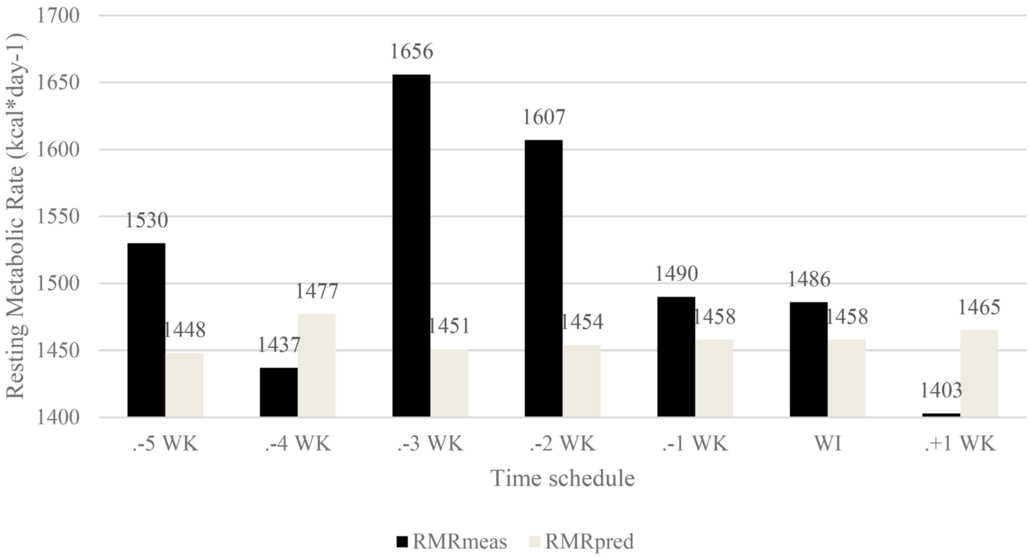


FIGURE 5
Resting metabolic rate and predicting resting metabolic rate. RMEmeas, resting metabolic rate measured; RMRpred, resting metabolic rate predicted (Cunningham); WK, week; WI, weigh in, and F, fight.

TABLE 4 Maximal power, average power, minimal power, relative average power, relative maximal power, the tendency to fatigue, fatigue rate, and total work.

| Critical power | Phase 2 | | Phase 3 | | | Phase 4 |
|---|---|---|---|---|---|---|
| | .–3 WK | .–2 WK | .–1 WK | WI | F | . + 1 WK |
| Duration | 240,00 | 240,01 | 240,01 | 240,01 | 240,00 | 240,01 |
| Maximal power | 392,63 | 313,66 | 294,03 | 302,76 | 285,08 | 304,49 |
| Avarage power | 204,51 | 200,28 | 192,00 | 169,36 | 192,73 | 194,37 |
| Minimal power | 159,89 | 145,87 | 140,38 | 90,47 | 128,12 | 146,78 |
| Avarage power/body weight | 3,57 | 3,50 | 3,35 | 3,15 | 3,46 | 3,45 |
| Maximal power/body weight | 6,85 | 5,47 | 5,13 | 5,64 | 5,12 | 5,41 |
| Tendency to fatigue | 1,05 | 5,48 | 3,28 | 1,23 | 0,84 | 2,23 |
| Fatigue rate | 59,28 | 53,49 | 52,26 | 70,12 | 55,06 | 51,79 |
| Total work | 49,04 | 48,07 | 46,04 | 40,61 | 46,22 | 46,61 |

For the −5 WK measurements, the bicycle ergometer VO2max test was initially chosen but was later replaced by the −4 WK critical power test. The critical power test (−4 WK) initially lasted 3 min, and due to an unclear indication of typical stress test fatigue, it was extended to 4 min. WK, week, WI, weigh-in, and F, fight, Phase 2 - fight camp diet, Phase 3 - fight week and Phase 4 - post-fight week.

reduction in RMR values by −253 kcal, with the most significant drop observed one week after the low EA (LEA) period. The decrease in basal metabolism associated with REDs has also been observed in Australian female athletes (26) and fighters (7, 17, 19). Furthermore, a study on Norwegian athletes identified several markers of REDs, including reduced basal metabolism (27). In terms of lipid profile, an increase in total cholesterol (+10%) and LDL (+8%) was noted, potentially influenced by Rapid Weight Loss (RWL) strategies in the last three days.

The athlete's performance declined, with a −27% reduction in maximal and a −6% reduction in average performance during the critical performance stress test. It is hypothesized that the decline would have been more pronounced if performance results were available before the LEA. Decreased performance was also noted in the fighters in the study by Barley et al. (28). Contrary to expectations based on the REDs syndrome definition by Mountjoy (16), the study revealed relatively moderate and less significant health changes in female athletes. Further research is needed to establish the critical lower limit for energy availability.

Despite the LEA during the fight camp, a modest FFM reduction of −0.6 kg occurred. This phenomenon is attributed to the inclusion of strength training and a protein intake of 2 g/kg Body Weight (BW), supported by previous research indicating that increased protein intake and strength training can maintain muscle protein synthesis rates under low energy availability (29). The reduction in FFM during fight camp was in the Kasper (7) and Evans (17) studies.

The cumulated energy deficit during Phase 2 was −23,058 kcal, theoretically leading to an expected post-phase weight loss of −3.3 kg. However, the real loss of adipose tissue measured by DXA was only −1.5 kg, partially explained by the athlete's history of attending multiple fight camps annually and her relatively low body fat percentage.

During Phases 2 and 3, markers of creatinine and urea increased, consistent with a study involving wrestlers who experienced similar increases during RWL strategies combined with high training loads (30, 31). Elevated values of these markers suggest acute kidney injury (AKI), emphasizing the need for education on avoiding RWL and maintaining adequate hydration in athletes.

The critical performance test during the fight week exhibited positive changes, with the female athlete's performance at −1

TABLE 5 Changes in blood clinical chemistry.

| Basic biochemistry | Phase 1 | Phase 2 | | Phase 3 | Phase 4 | | avrg. |
|---|---|---|---|---|---|---|---|
| | CW | .−4 WK | .−2 WK | WI + F | . + 1 D | . + 1 WK | |
| Na (mmol/L) | 140 | 142 | 141 | 144 | 141 | 139 | 136–145 |
| K (mmol/L) | 4,8 | 5 | 4,7 | 4,2 | 4,5 | 4,7 | 3,5–5,2 |
| Cl (mmol/L) | 106 | 106 | 107 | **110** | 107 | 104 | 98–107 |
| Urea (mmol/L) | 6 | 7,3 | **7,5** | **11,8** | 6,9 | 8,5 | 2,5–7,4 |
| Creatinine ($\mu$mol/L) | 74 | **82** | **104** | **99** | **90** | 75 | 44–80 |
| CRP (g/L) | <1 | <1 | <1 | <1 | <1 | <1 | 0,0–5,0 |
| Total protein (g/L) | 74,4 | 71,7 | 76 | 80 | 68 | 69 | 64,0–83,0 |
| Albumin (g/L) | 48 | 47 | 49 | 51 | 43 | 45 | 35–52 |
| P-osm (nmol/kg) | 291 | 292 | 291 | **296** | 286 | 293 | 275–295 |
| Diabetology | | | | | | | |
| Plasma glucose (mmol/L) | 5,2 | 4,5 | 4 | 4,4 | 4,8 | 4,7 | 3,5–5,6 |
| Insulin | x | 2,9 | 3,5 | 3,4 | 2,5 | 2,7 | 2,6–25,0 |
| Lipid profiles | | | | | | | |
| Total cholesterol (mmol/L) | **5,6** | **5,4** | 5,7 | **6,2** | **5,2** | **5,4** | 2,9–5,0 |
| HDL (mmol/L) | 1,9 | 1,9 | 2,2 | 2 | 1,9 | 1,8 | 1,2–2,7 |
| LDL (mmol/L) | **3,6** | **3,5** | 3,5 | **3,9** | **3,3** | **3,5** | 1,2–3,0 |
| Triglyceride (mmol/L) | 0,63 | 0,61 | 0,52 | 0,72 | **0,44** | 0,68 | 0,45–1,70 |
| Iron metabolism | | | | | | | |
| Sol.transferin receptor (mmol/L) | x | 16,5 | 17,2 | 18,3 | 13,8 | 15,4 | 0,0–21,0 |
| Transferrin (g/L) | x | 2,76 | 2,9 | 2,95 | 2,44 | 2,55 | 2,0–3,6 |
| Ferritinin (µg/L) | 16,3 | 19,8 | 15,9 | 15,5 | 16,9 | 14,8 | 4,6–204,0 |
| Thyroid gland | | | | | | | |
| TSH (mU/L) | 3,681 | 2,392 | 2,619 | 2,075 | 2,544 | 3,328 | 0,270–4,20 |
| T4 free (pmol/L) | 10,1 | 10 | 10,4 | 10,1 | 9,3 | 10,1 | 9,0–19,0 |
| T3 free (pmol/L) | 3,7 | 2,9 | 2,8 | 2,7 | 2,8 | 3,5 | 2,6–5,7 |
| Cardiac markers | | | | | | | |
| CK (µkat/L) | 2,54 | 2,36 | 2,21 | 2,39 | 1,89 | 2,54 | 0,20–2,85 |
| Bone turnover | | | | | | | |
| vit. D (nmol/L) | **44,4** | **45,5** | **57,5** | **60,9** | **53,4** | **56** | 75–200 |
| Beta-crosslaps (hg/L) | **907** | **838** | **708** | **777** | **703** | **631** | 0–573 |
| P1NP (µg/L) | **97** | **94** | **91** | 74 | **81** | **90** | 15–74 |
| Hormones | | | | | | | |
| FSH (U/L) | x | 6,1 | 3,7 | 4,3 | 4,1 | 6,3 | |
| LH (U/L) | 2,7 | 2,3 | 0,3 | 0,4 | 0,3 | 1 | |
| Estradiol (pmol/L) | <34 | <34 | <34 | <34 | <34 | 87 | |
| Prolactin (mlU/L) | 373,1 | 418,9 | 255,6 | 152 | 329,4 | 324,8 | 109–557 |
| SHBG (nmol/L) | 47,5 | 47,1 | 53,8 | 54,1 | 48,1 | 44,5 | 26–110 |
| Cortisol (nmol/L) | 525 | **557** | **541** | 501 | 461 | **544** | 101–536 |
| IGF-1 (µg/L) | 188 | 218 | 180 | 175 | 151 | 203 | 103–326 |
| Testosterone (nmol/L) | x | 0,93 | 1,09 | 0,97 | 0,86 | 1,05 | 0,29–1,67 |

CW, control week; WK, week; WI, weigh in; F, fight; Na, sodium; K, calcium; Cl, chloride; CRP, c-reactive pro-tein; P-osm, plasma osmolality; HDL, high-density lipoprotein; LDL, low-density lipoprotein; TSH, thyroid stimulating hormones; T4, thyroxine; T3, triiodothyronine; CK, creatine kinase; vit. D, vitamin D; P1NP, type 1 procollagen amino terminal peptides; FSH, follicle stimulating hormone; LH, luteinizing hormone; SHBG, sex hormone binding globulin, and IGF-1, insulin-like growth factor. avg., average, Phase 1 – control week, Phase 2 - fight camp diet, Phase 3 - fight week, and Phase 4 - post-fight week.

WK being restored between the weigh-in and the fight. However, from an overall perspective, negative changes persisted, with the maximum performance of −3 WK being 25.3% higher than in the fight week. The decrease in power output during LEA, affecting glycogen stores and, subsequently, power output, is undesirable in combat sports, where peak performance is crucial during a fight. The results of the critical power test measured during fight week are similar to a study by Mendes (13), where they measured the effect of RWL use on fighters' performance. The fighters reduced BW by 5% over 5 days after a 4-hour window after weigh-ins to rehydrate their bodies and replenish nutrients. The study showed no negative effect of RWL on intermittent high-intensity exercise.

A comparison with studies by Kasper (7) and Langan-Evans (17) indicates that the unique conditions in this case study provided ecologically valid settings. Real-life training was simulated as closely as possible, allowing immediate post-weigh-in and pre-fight testing. The findings highlight the need for further research to understand the complex interactions between diet, training, and performance in combat sports.

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The study showed that RWL and CWL strategies led to the development of RED syndrome symptoms during fight camp. Specifically, these included a decrease in BMR values, an increase in urea and creatine levels, a decrease in critical performance test performance, and a calculation of energy intake. Markers related to basal metabolic rate, bone density, anthropometric indices, T3 levels, sex hormones, and calculated energy intake are often used to diagnose REDs (16, 32).

This case study, despite yielding helpful information about the physiological and performance implications of weight cycling in a female Muaythai athlete, is hampered by its single-subject design. Findings cannot be generalized to all female combat sport athletes due to variability among individuals in training history, physiological adaptation, and prior experience with weight-cutting protocols. Absence of a control group constrains inference regarding separation of fight camp protocol-induced adaptations from others due to other external or cumulative factors of training. In addition, while test fight conditions were attempted to replicate competitive settings in life, absence of actual fighting may have impacted psychological and physiological responses. Lastly, the limited length of post-fight observation limits the comprehension of long-term recovery and potential late effects of decreased energy availability. Increased sample sizes, variability, and monitoring time posts-competition in future studies would be advantageous.

## 5 Conclusions

This case study explored the effects of a five-week fight camp diet characterized by low EA (LEA) on health and performance parameters in the context of REDS of a female Muaythai athlete. The athlete experienced weight loss, with notable manifestations such as reduced RMR and altered lipid profiles. Performance metrics indicated a decline in maximal and average performance during a critical performance stress test. Contrary to expectations, the study revealed relatively moderate health changes, emphasizing the need for further research to establish critical lower limits for energy availability in combat sports.

Despite low energy availability (LEA), the athlete experienced only a minimal decline in FFM, likely due to the incorporation of targeted resistance training and sufficient protein intake throughout the intervention. Notably, the calculated energy deficit exceeded the observed adipose tissue reduction, suggesting the influence of individual moderating factors, including prior experience with repeated weight cuts and inherently low body fat levels.

Elevations in serum creatinine and urea during the RWL phase indicate transient renal stress, highlighting the physiological risks associated with aggressive weight-cutting strategies and reinforcing the importance of proper hydration protocols. Although partial performance recovery was observed following weigh-in, baseline values were not fully restored, underscoring the fragile equilibrium between LEA, physiological recovery, and functional capacity in combat sports preparation.

The ecological validity of this study—rooted in real-world training, dietary practices, and performance testing closely replicating pre-competition conditions—adds practical relevance to the findings. These insights contribute to the ongoing discourse on safe weight management in athletes and reinforce the need for evidence-based, individualized guidelines to safeguard health while maintaining competitive performance. Further research should prioritize sex-specific physiological responses and long-term adaptations to LEA in combat sport contexts.

## Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

## Ethics statement

The studies involving humans were approved by The case study received approval from the Research Ethics Committee of Masaryk University (EKV-2021-004). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

## Author contributions

VB: Methodology, Data curation, Writing – review & editing, Writing – original draft, Project administration, Formal analysis. AW: Writing – review & editing, Visualization, Conceptualization. MK: Methodology, Supervision, Writing – review & editing, Project administration.

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## Conflict of interest

The 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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# Effects of high-intensity interval training on executive functions and IGF-1 levels in sedentary young women: a randomized controlled trial

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**Purpose:** Sedentary behavior and physical inactivity are widespread among university students, negatively impacting physical and neurocognitive health. Executive functions and insulin-like growth factor 1 (IGF-1) are adversely affected by inactivity. Moreover, physical activity increases IGF-1 concentrations, which may mediate beneficial effects on brain health and cognitive performance. The effect of HIIT exercise combined with increased physical activity on these variables is not well understood. This study evaluated the chronic effects of HIIT, with or without increased physical activity, over 12 weeks of training and a 12-week follow-up period, on executive functions and IGF-1 concentrations in sedentary young university students.

**Method:** This randomized controlled trial included 77 sedentary female university students, assigned to three groups: HIIT ($n = 25$), HIIT plus increased daily physical activity (HIIT + PA, $n = 25$), and control group (CG, $n = 27$). The intervention involved assessments at baseline (T1), post-intervention (T2), and after a 12-week follow-up (T3). Salivary IGF-1 concentrations were measured using enzyme-linked immunosorbent assay (ELISA). Executive functions were evaluated with the Stroop Test, Wisconsin Card Sorting Test, and Digit Span Test. The HIIT protocol consisted of 40-min sessions, three times per week, delivered online. The HIIT + PA group also aimed to complete 10,000 steps per day.

**Results:** No statistically significant changes in IGF-1 concentrations were found over time or between groups, although descriptive increases were observed in both HIIT and HIIT + PA groups at follow-up. For executive functions, improvements over time were found in cognitive flexibility (WCST) and working memory (DST-B and DST-T), but without significant group × time interactions. Only WCST-E-P showed a significant group effect ($p = 0.028$), indicating possible differences between groups in cognitive rigidity. The HIIT + PA group showed a tendency toward improved inhibitory control (Stroop accuracy), although this was not supported by significant interaction effects. Working memory improvements (DST-B) were significant over time, especially in the HIIT group, but again without significant differences between groups.

**Conclusion:** A 12-week HIIT program, with or without increased daily physical activity, can lead to improvements in executive functions in sedentary young women, particularly in working memory and cognitive flexibility. However, these changes were not exclusive to the intervention groups, suggesting possible contributions from repeated testing or other external factors. While IGF-1 levels showed upward trends, no significant group-level effects were confirmed. These findings highlight the potential cognitive benefits of HIIT but emphasize the need for further research with tighter controls and objective neurobiological measures to clarify the mechanisms involved. Incorporating HIIT into student routines may support cognitive health, but broader lifestyle interventions may be needed to sustain long-term benefits.

KEYWORDS

executive functions, HIIT, IGF-1, women, sedentary behavior

## Introduction

Sedentary behavior and physical inactivity are prevalent issues among young populations, particularly among university students. The transition to university life often involves increased academic and social responsibilities, which frequently lead to a decrease in regular physical activity. This sedentary lifestyle has significant health implications, not only at a physical level but also at a neurocognitive level (1).

Executive functions—a set of high-order cognitive processes including inhibitory control, working memory, and cognitive flexibility—are particularly sensitive to physical activity levels (2). These functions are critical for academic success, self-regulation, and goal-directed behavior. Numerous studies indicate that physical inactivity negatively impacts these cognitive domains. In contrast, regular physical activity has been shown to enhance executive functioning (2).

One key mediator proposed in the relationship between physical activity and brain function is insulin-like growth factor 1 (IGF-1). IGF-1 is a neurotrophic and neuroprotective hormone involved in synaptic plasticity, neurogenesis, and neuronal survival (3). Although not typically used in clinical cognitive assessments, growing evidence suggests that IGF-1 levels correlate with cognitive performance. This is especially evident in domains associated with the prefrontal cortex and hippocampus—regions critical for executive functions. For example, higher peripheral IGF-1 concentrations have been linked to better performance on attention, memory, and processing speed tasks in both aging and young adult populations (4). Moreover, experimental studies show that physical activity induces the expression and release of IGF-1 from peripheral tissues. This circulating IGF-1 can cross the blood–brain barrier and promote brain plasticity (5). This mechanistic link supports the use of IGF-1 as a biological marker of cognitive health and physical activity efficacy, even in young populations where cognitive decline is not clinically apparent (6).

In addition to IGF-1, it is important to recognize that the relationship between physical activity and cognitive health is complex and mediated by multiple, interconnected biological mechanisms. These include the release of brain-derived neurotrophic factor (BDNF), which supports synaptic plasticity and neurogenesis, as well as increased cerebral blood flow, which enhances oxygen and nutrient delivery to key brain regions. Furthermore, exercise-induced structural changes in the hippocampus and prefrontal cortex—areas critically involved in executive functioning—also contribute to cognitive improvements. These mechanisms work synergistically and vary depending on the intensity, duration, and type of physical activity (7). IGF-1 was selected in this study as a relevant and accessible biomarker due to its neurotrophic properties and its responsiveness to exercise. However, it is not the only nor necessarily the most definitive indicator of cognitive outcomes.

High-Intensity Interval Training (HIIT) has emerged as a particularly effective exercise modality for improving these variables. HIIT is characterized by brief periods of high-intensity exercise alternated with recovery periods. It has been shown to improve both executive functions and IGF-1 levels more efficiently than sustained moderate-intensity exercise (4). However, despite its benefits, exercise programs often face the challenge of poor adherence, especially among young populations (5).

To address this barrier, it is crucial to develop exercise programs that are short, flexible, and can be performed at home (4). Combining physical activity with HIIT presents a promising strategy to foster adherence and maximize cognitive and neurophysiological benefits in sedentary young individuals. Increasing the number of daily steps has been consistently associated with improvements in executive functions (8). Regular physical activity, such as walking, induces structural and functional changes in the brain, particularly in areas associated with executive functions like the prefrontal cortex and the hippocampus (9). Light-intensity physical activity stimulates the production of brain-derived neurotrophic factor (BDNF), which promotes neurogenesis and synaptic plasticity. These processes are essential for memory and learning (10). In addition, walking enhances cerebral blood flow. This improves the delivery of oxygen and nutrients to the brain, thereby supporting cognitive health (11). Thus, incorporating walking into daily routines is practical and effective, promoting cognitive health through simple lifestyle changes.

In this context, our research aims to evaluate the chronic effect of high-intensity interval training on executive functions and IGF-1 concentration in young sedentary university students. Based on the preceding findings, it is hypothesized that the intervention groups, especially the HIIT + PA group, will experience a more significant improvement in cognitive functions and IGF-1 levels compared to the control group, due to the combined effects of HIIT and the increase in daily physical activity.

This study is expected to provide evidence on the effectiveness of accessible and flexible HIIT programs, contributing to the formulation of more effective intervention strategies for this population.

# Methods

## Study population

The current study adopts a controlled and randomized experimental design (RCT), employing a sequential approach with three parallel groups and repeated measures assessed at pretest (T1), post-test (T2), and following the conclusion of the follow-up period (T3). All variables were measured at three time points. At the beginning of the training program (T1), after 12 weeks of the HIIT program (T2), and following a 12-week follow-up period (T3) to assess the residual effect.

The study population consisted of healthy and sedentary female university students (22 ± 1.1 years) who did not engage in regular physical activity, defined as less than 150 min of moderate physical activity per week (IPAQ) (12). Sedentary status was determined through a self-reported physical activity questionnaire administered during the initial screening process, where participants confirmed performing less than the recommended 150 min of moderate-intensity activity per week, in line with WHO guidelines.

Inclusion criteria were as follows: (1) age between 18 and 25 years; (2) reflect in the IPAQ questionnaire to be in category 1 or low level of physical activity (12) and therefore not conforming to the minimum recommendations for PA and physical exercise; (3) no diagnosis of neurological, cardiovascular, or metabolic conditions; (4) not taking medications that could affect cognitive function; and (5) commitment to participate in the entire intervention and assessment process. Exclusion criteria included: (1) regular participation in structured exercise programs in the last 6 months; (2) current pregnancy or breastfeeding; and (3) failure to attend at least 80% of the scheduled training sessions; (4) bilingualism. The habitual and indistinct use of two or more languages and (5) playing a musical instrument regularly and continuously, as in the previous criterion, has a positive effect on the subject's cognition.

Sample size estimation was conducted using G*Power 3.1 software. To ensure the validity and generalizability of the results, the sample size was calculated based on the main outcome variable: salivary IGF-1 levels in response to high-intensity physical exercise. The study by Antonelli et al. (13) was used as a reference due to its methodological similarity and comparable sample characteristics. Based on this, a minimum of 25 participants per group was determined to be necessary, assuming a 95% confidence level ($\alpha = 0.05$) and a statistical power of 90%. The sample was increased to 77 participants at baseline to account for potential dropouts.

The initial recruitment aimed to enroll 77 sedentary college women meeting these criteria. After completing the intervention and full assessment process, the final evaluated population consisted of 58 women. Thus, the total number of women included in the final analyses was 20 for the high-intensity interval group (HIIT), 21 for the high-intensity interval group plus physical activity (HIIT + PA), and 17 in the control group (CG). All participants provided written informed consent.

The control group (CG) was instructed to maintain their usual daily routines without engaging in any structured physical activity. Weekly check-ins were conducted to ensure adherence and to confirm no additional interventions were introduced.

Following the 12-week intervention, all groups entered a 12-week follow-up period without structured training or supervision. The purpose was to evaluate whether the effects of the HIIT and HIIT + PA interventions persisted once active supervision ceased.

A detailed account of cohort recruitment and study procedures has been previously documented and published (14), with reference to the ClinicalTrials.gov Identifier: NCT05642169. This study protocol was reviewed and approved by the Ethics Committee for Research Ethics Committee of the Virgen Macarena-Virgen del Rocío University Hospitals (2038-N-20).

## Randomization and blinding

A computer-generated simple randomization sequence was used to assign participants to the HIIT program (HIIT), HIIT plus increased daily physical activity (HIIT + PA) or control group (CG) after the first assessment. Members of the research team involved in the assessments and the data analysis were blinded to the group allocation.

Additionally, the psychologist responsible for administering the cognitive assessments was blinded to the participants' group assignment to prevent assessment bias. Participants were informed they were involved in a study comparing the effects of different physical activity protocols but were not made aware of the specific hypotheses or which intervention was expected to produce greater cognitive benefits. This partial concealment minimized expectancy effects and performance bias.

A total of 77 women were randomized into the HIIT ($n = 25$), HIIT + PA ($n = 25$) or CG ($n = 27$). Subsequently, participant signed a written informed consent before taking part in the study.

# Procedures

## Exercise groups and increase in physical activity

The training sessions occurred three times a week (Monday, Wednesday, and Friday) over a period of 12 weeks. The intervention groups were divided into 5 groups, each consisting of approximately 10 participants. The training sessions were conducted online, with a coach monitoring the physical actions to ensure proper intensity and technique correction. The exercise program consisted of a 10 min warm-up period with mobility and dynamic stretching exercises, a progressive main part ranging from 24 to 36 min, and a 5-min cool-down with stretching and relaxation. The main part followed a HIIT structure with a density of 1:1 (30 s of exercise and 30 s of rest).

The training programme started at an intensity of 8 on the Borg scale for the first 3 weeks. This first phase served as an adaptation period. Once this first period was completed, 3 weeks were carried out at an intensity of 8.5. This was then increased by 0.5 every 2 weeks until maximum effort was achieved during the last 2 weeks.

The training program followed a progressive overload model: during the first 3 weeks, participants trained at an RPE of 8 (vigorous intensity), which increased progressively toward the final 2 weeks, when participants reached maximum intensity (RPE 9–10).

Full details on the training programme and its progression were published in the following study (14).

In addition to HIIT, the HIIT + PA group was required to achieve a daily goal of at least 10,000 steps. To monitor this, all participants in this group wore wrist-worn physical activity trackers, and the number of daily steps was recorded at the end of each day. Participants submitted these records through a digital platform monitored by the research team.

To support adherence, individualized feedback was provided regularly based on step counts, and specific strategies were implemented to help participants reach their daily goal. These included motivational messages, practical recommendations to increase incidental activity (e.g., walking instead of taking the elevator or public transport), and behavioral prompts during the day.

The number of daily steps was recorded for each participant, and weekly reports were generated. While most participants successfully reached the target on most days, the level of compliance varied slightly across individuals. These deviations were considered in the analysis and reported in the adherence section of the study.

The control group (CG) did not receive any intervention. Participants in this group were instructed to maintain their usual daily routines and refrain from starting any new structured physical activity programs during the study period. They were not provided with guidance or supervision related to physical activity, and their activity was not externally monitored. This group served as a baseline comparison to evaluate the effects of the HIIT and HIIT + PA interventions.

## Measured outcomes

All the variables listed below were recorded at 3 moments (T1, T2 and T3).

### Body composition variables

Body composition variables (fat mass and muscle mass) were estimated using segmental bioelectrical impedance analysis (BIA) with a Tanita BC-418 device (Tokyo, Japan), a valid and reliable non-invasive method (15). Measurements were taken under standardized conditions, including at least 4 h of fasting, avoidance of intense exercise and caffeine, and urination 30 min before the test (Table 1).

### Biochemical determinants

Saliva samples were collected under standardized conditions at three time points: baseline (T1), post-intervention (T2), and post-follow-up (T3). All samples were collected early in the morning (between 9:00 and 10:00 a.m.) after an overnight fast of at least 8 h. This protocol was applied uniformly to all participants to control for circadian and dietary influences on salivary biomarkers. Saliva samples were collected under fasting conditions in the early morning, using the passive drool method, which has been shown to provide reliable hormone quantification (16). After collection, the samples were centrifuged at 1,500 g for 15 min and stored at −80°C. IGF-1 levels were determined using enzyme-linked immunoassays (ELISA) according to the manufacturer's protocol (Elabscience, USA), and all samples were measured in duplicate.

The decision to use salivary IGF-1 instead of serum was based on considerations of feasibility and non-invasiveness, particularly given the study population of young, healthy individuals. Salivary collection methods reduce participant burden, increase compliance, and allow for repeated measures without the need for venipuncture. Furthermore, recent studies have demonstrated a significant correlation between salivary and serum IGF-1 levels, supporting its validity as a biomarker in exercise-related interventions (17, 18). Thus, salivary IGF-1 represents a practical and sufficiently sensitive alternative for assessing endocrine responses to physical activity in field-based and non-clinical research settings.

Saliva was collected in a fasting state using the passive drooling method, then centrifuged and stored at −80°C. Enzyme-linked immunoassays (ELISAs) were used to measure IGF-1 concentration in duplicate. Samples were added to microplate wells with specific antibodies and incubated with Avidin conjugated with Horseradish Peroxidase (HRP). Only wells containing IGF-1 showed a color change when 3,3′, 5,5′-Tetramethylbenzidine (TMB) substrate solution was added. Colorimetric changes were

TABLE 1 Anthropometric characteristics of the participants at baseline (Mean ± SD).

| Variable | HIIT ($n$ = 20) | HIIT + PA ($n$ = 21) | CG ($n$ = 17) |
|---|---|---|---|
| Weight (Kg) | 61.95 ± 15.3 | 58.59 ± 9.6 | 62.52 ± 8.6 |
| Height (cm) | 163.9 ± 4.6 | 161.2 ± 5.8 | 161.1 ± 5.2 |
| Fat mass (%) | 30.22 ± 8.9 | 30.27 ± 6.4 | 31.78 ± 5.5 |
| Muscle mass (Kg) | 40.1 ± 4.2 | 38.3 ± 3.2 | 40.1 ± 3.5 |

HIIT, high interval intensity training group; HIIT + PA, high interval intensity training group plus increase of physical activity; Mean ± standard deviation; CG, control group.

induced by TMB substrate in the presence of IGF-1 and quantified using a standard curve. Concentration was determined by comparing with a standard curve using Elabscience kits (Elabscience Biotechnology Inc.)

Although salivary IGF-1 represents the unbound (free) fraction of circulating IGF-1, previous research indicates that it correlates meaningfully with systemic levels, particularly in response to acute physical activity (17). This supports its use as a non-invasive and reliable biomarker in young, healthy individuals undergoing physical training.

### Executive functions

The measurements of executive functions were carried out with the collaboration of a psychologist specialized in neurocognitive testing. Three standardized test tests were used:

The Stroop Test (ST) was employed to evaluate inhibitory control, utilizing a digitized version (19). This brief assessment measures interference during task performance. Variables such as time and the number of intrusion errors resulting from inhibitory control failures were assessed.

The Wisconsin Card Sorting Test (WCST) primarily assesses cognitive flexibility (20). This test involves 64 cards with various combinations. Measured variables include the number of correct responses, identified categories, perseverative responses, set maintenance failures, among others. The WCST has demonstrated high reliability and validity (21).

Finally, the Digit Span Test (DST) measures working memory. It consists of two measures: forward and backward. The number of digits reached without errors, both in forward and backward order, is evaluated (22). The outcomes are summarized in Table 2 along with other dependent variables.

All assessments followed standardized administration procedures to ensure reliability, and references have been added to support the validity of the tests used. Participants were scheduled at the Exercise Laboratory of the University of Seville. After following the standardized protocol the previous day, they first underwent height and body composition assessments. This was followed by 5 min of seated rest to ensure a resting state before saliva collection using the passive drool method (5 ml into sterile polypropylene tubes). Finally, executive functions were assessed using the ST, WCST, and DST.

TABLE 2 Summary of variables related to executive function.

| Stroop test (ST) | Nomenclature |
|---|---|
| Interference time | ST-I-T |
| Interference correct responses | ST-I |
| **Wisconsin card test (WCST)** | |
| Correct categories | WCST-C |
| Correct responses | WCST-R |
| Perseverative error | WCST-*P*-E |
| **Digit span test (DST)** | |
| Forward memory | DST-F |
| Backward memory | DST-B |
| Total correct responses (forward + backward) | DST-T |

### Statistical analysis

Once the data were obtained from the three research groups (HIIT, HIIT + PA, and CG), they were compared at the beginning, after 12 weeks of intervention, and 12 weeks after the end of the training program. Only women who attended at least 80% of the exercise sessions were included in the statistical analyses. To assess intergroup differences in parametric variables, a one-way ANOVA with three levels was conducted. If significant differences in means between groups were observed, the *post hoc* Bonferroni test was employed to identify the specific group(s) showing differences. In cases of unequal variances, the T3 Dunnett test was utilized. For variables that did not meet the assumption of normality, the non-parametric Kruskal–Wallis test was performed. If significant differences were detected, the Mann–Whitney test was applied to evaluate differences between groups.

Within-group comparison was conducted to contrast differences between groups after the intervention. For variables that met normality, repeated measures ANOVA was applied, and for those that did not, Friedman and Wilcoxon signed-rank tests were used. Cohen's criteria (23) were followed for effect size analysis. Prior to the main analysis, the dataset was screened for outliers using a ± 3 standard deviation criterion. In the Digit Span Backward (DST-B) variable, three extreme values were identified and excluded from the analysis All data were analyzed using SPSS v.26 (IBM Corp., Armonk, NY, USA), with a confidence interval of 95%, and a significance level of $p \leq 0.05$.

## Results

Once the sample was selected, it consisted of a total of 77 subjects (HIIT + PA, $n = 25$; HIIT, $n = 25$; GC, $n = 27$). After completing the entire training period and follow-up, due to dropouts at some point in the research, the final analyzed sample was of 58 women (HIIT + PA, $n = 20$; HIIT, $n = 21$; GC, $n = 17$) (Figure 1).

Focusing on the main study variable, the initial concentration of the 3 groups showed no significant between-groups differences ($p = 0.336$). Regarding executive functions (ST, WCST, and DST), no differences between groups were found in each executive function at the baseline ($p > 0.05$). Only DST-B showed differences between groups at baseline ($p = 0.02$).

For salivary IGF-1 concentration, the repeated measures ANOVA did not show significant effects for time ($p = 0.501$), group ($p = 0.677$), or group × time interaction ($p = 0.404$), suggesting no robust differences across conditions or over time at the group level. Despite this, descriptive data show numerical increases in IGF-1 levels in the HIIT and HIIT + PA groups between T1 and T3 (e.g., HIIT mean from 1.1 to 3.4 ng/ml; HIIT + PA from 1.1 to 3.4 ng/ml), whereas the control group remained relatively stable (from 1.7 to 2.3 ng/ml).

These increases, however, should be interpreted with caution given the high variability in the T3 data (standard deviation = 4.6

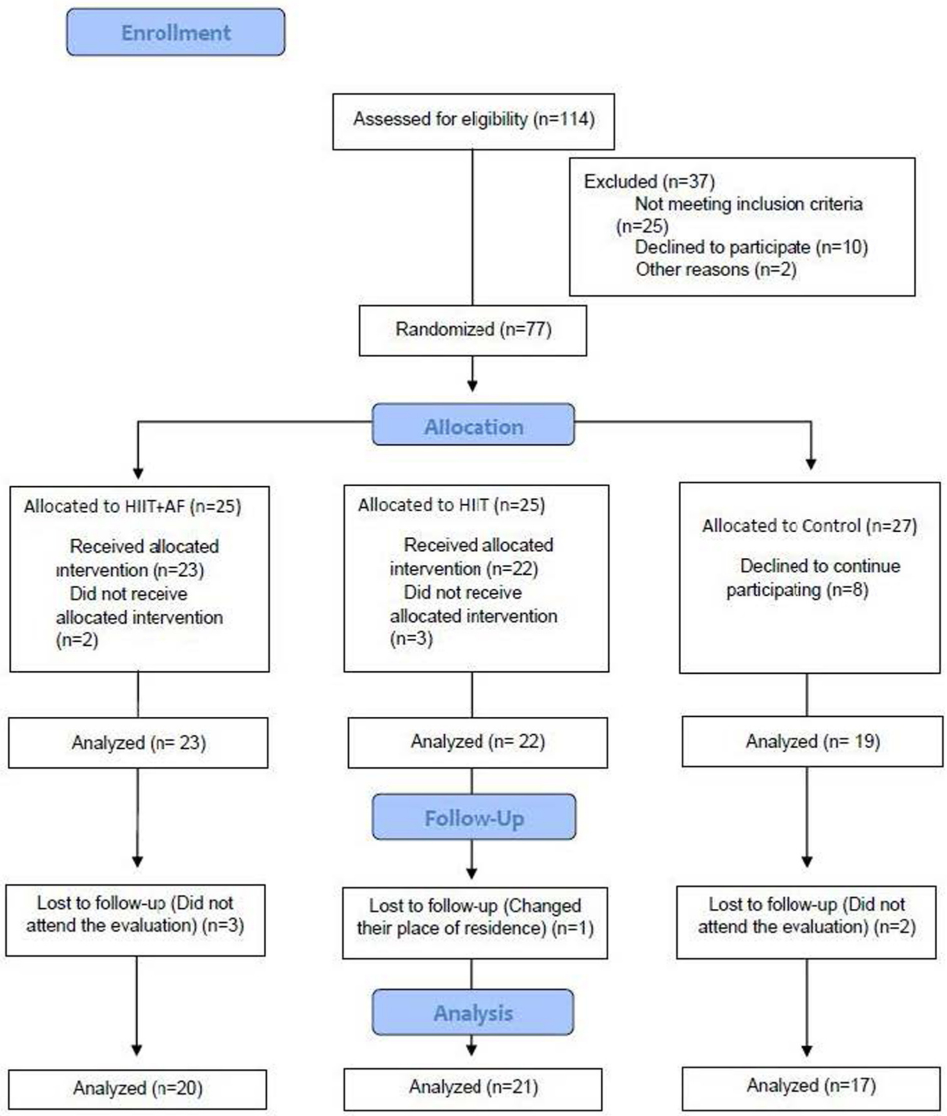


FIGURE 1
Flowchart represents different stages in the research process.

in both intervention groups) and the non-significant overall effects. As such, the pairwise or within-group comparisons are presented for descriptive purposes only and should not be interpreted as confirmatory evidence of effectiveness.

Although no significant group or interaction effects were found in the repeated measures ANOVA for IGF-1 concentration (group $p = 0.677$; interaction $p = 0.404$), significant changes over time were observed in the within-group analyses (Table 3) were observed in both the HIIT and HIIT + PA groups (HIIT: $p = 0.002$, $d = 0.96$, $\Delta = 29.6$; HIIT + PA: $p \leqq 0.001$, $d = 0.78$, $\Delta = 28.8$). When observing the residual effect 3 months after the conclusion of the training program, only the HIIT ($p = 0.036$, $d = 0.42$, $\Delta$ 50.5%) and HIIT + PA groups ($p = 0.03$, $d = 0.48$, $\Delta$ 77.3%) demonstrated significant changes in IGF-1 concentration compared to the CG.

In terms of inhibitory control (ST) (Table 4), a significant effect of time was observed in the ST-I-T (interference time) variable, reflecting an overall reduction in completion time across the sample from T1 to T2 and T3 ($p < 0.001$). However, no significant group ($p = 0.732$) or group $\times$ time interaction effects ($p = 0.563$) were found, suggesting that improvements were not specific to any intervention group.

Descriptively, both the HIIT and HIIT + PA groups exhibited reductions in interference time—HIIT from 37.5 s to 29.8 s, and HIIT + PA from 33.5 s to 28.4 s—while the control group also improved from 37.9 s to 34.5 s. These reductions persisted at follow-up (T3).

For the number of correct responses (ST-I), only the HIIT + PA group showed a significant effect over time ($p = 0.003$). However, group ($p = 0.116$) and interaction ($p = 0.126$) effects were not significant, indicating that the improvement in accuracy is likely not attributable to the intervention *per se*.

TABLE 3 IGF-1 salivary concentration at the three evaluation timepoints T1, T2, and T3 ($n = 58$).

| Variable | Group | T1 Media (sd) | | T2 Media (sd) | | T3 Media (sd) | | P valor time | $\eta^2$ partial | P valor group | $\eta^2$ partial | P valor group*time | $\eta^2$ partial |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| IGF-1 (ng/ml) | HIIT | 1.1 | (0.3) | 1.5 | (0.3) | 2.4 | (2.4) | 0.001* | | 0.845 | | 0.817 | |
| | HIIT + PA | 1.2 | (0.1) | 1.5 | (0.5) | 2.5 | (2.0) | | 0.23 | | 0.01 | | 0.01 |
| | CG | 1.1 | (0.1) | 1.6 | (0.5) | 2.0 | (1.3) | | | | | | |

Ng, nanogram; SD, standard deviation; ml, milliliter.
*Significant differences ($P < 0.05$).

TABLE 4 Differences between different phases and groups in TS at time T1, T2 and T3.

| Variable | Group | T1 Media (sd) | | T2 Media (sd) | | T3 Media (sd) | | $p$ valor time | $\eta^2$ partial | $p$ valor group | $\eta^2$ partial | $p$ valor group*time | $\eta^2$ partial |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ST- I -T (s) | HIIT | 37.5[a,b] | (16.0) | 29.8 | (7.45) | 29.7 | (7.6) | <.001* | | .387 | | .542 | |
| | HIIT + PA | 33.5[a] | (11.1) | 28.4 | (10.1) | 28.9 | (11.6) | | .208 | | .034 | | .027 |
| | CG | 37.9[b] | (12.0) | 34.5 | (11.3) | 31.2 | (8.3) | | | | | | |
| ST- I (N° correct responses) | HIIT | 28.1[b] | (4.5) | 27.0 | (2.8) | 26.2 | (1.8) | .520 | | .280 | | .138 | |
| | HIIT + PA | 26.8 | (3.6) | 27.5 | (3.0) | 27 | (3.5) | | .012 | | .045 | | .061 |
| | CG | 26.1 | (2.9) | 25.6 | (1.6) | 26.2 | (1.6) | | | | | | |

S, seconds; SD, standard deviation; ST, stroop test; ST-I-T, total time; ST-I, number of correct responses.
*Significant differences ($P < 0.05$).
[a]Significant differences between T1 and T2.
[b]Significant differences between T1 and T3.

It is important to highlight that while these statistical improvements are significant, their practical impact on daily functioning, academic performance, or other real-world activities remains uncertain. Future studies could explore whether such changes in inhibitory control translate into meaningful cognitive benefits outside of the laboratory setting.

Regarding cognitive flexibility, significant time effects were observed in both WCST-C ($p = 0.013$) and WCST-R ($p = 0.001$), indicating improvements over time in the number of completed categories and correct responses. However, no significant group or interaction effects were found for either variable (all $p > 0.6$), suggesting that these improvements were not specific to the intervention groups.

For WCST-E-P (Perseverative Errors), a significant group effect was found ($p = 0.028$), indicating overall differences between groups, but no significant time or group × time interaction effects were observed. This suggests that although groups differed in the number of perseverative errors, these differences were not clearly driven by the training program.

The improvements in cognitive flexibility, although statistically significant, suggest potential benefits in executive functioning, which might influence tasks requiring adaptability, such as problem-solving or decision-making, which are essential for academic and professional settings

In the working memory domain (Table 6), the DST-B (Digit Span Backward) revealed a significant main effect of time ($p < 0.001$, $\eta^2 = 0.953$), indicating improvements across all groups. However, neither the group effect ($p = 0.843$) nor the group × time interaction ($p = 0.286$) were statistically significant, suggesting the changes were not specific to any intervention.

For the DST-F (Forward), no significant time effect was observed ($p = 0.565$), nor were there significant differences between groups ($p = 0.320$) or interaction effects ($p = 0.531$).

The DST-T (Total) showed a significant time effect ($p = 0.001$), but similar to the other measures, the group × time interaction was not significant ($p = 0.081$). Improvements in the HIIT group between T1 and T2 ($\Delta = 1.3$ points) were numerically notable, but cannot be attributed to the intervention with statistical certainty.

## Discussion

The purpose of the present study was to test the hypothesis that a 12-week HIIT program implemented with an increase in daily PA (HIIT + PA) enhances, to a greater extent, both IGF-1 concentration and executive functions in sedentary young women than a similar program (HIIT) but not implemented.

Furthermore, after 12 weeks following the completion of the training, these same variables measured would remain above that observed at baseline.

The results show how a 12-week HIIT training program can significantly improve IGF-1 concentration in sedentary young college women. In addition, it was observed that the improvements were increased to a greater extent after the follow-up evaluation, with the HIIT + PA group obtaining a higher percentage of change.

On the other hand, with respect to executive functions, only the HIIT + PA group obtained greater efficiency in inhibitory control (ST) after the training program. Regarding cognitive flexibility

(WCST), there are certain improvements in the HIIT and HIIT + PA groups after the HIIT program, but it is after the Follow-up when the HIIT + PA group shows a higher performance. Regarding working memory, the HIIT group obtained a significant change after the training program and after the follow-up period in the DST backward test (DST-B), which requires a greater demand on working memory.

## Changes in IGF-1

Our results did not show statistically significant changes in IGF-1 concentrations over time or between groups. Although descriptive increases were observed in the HIIT and HIIT + PA groups at the three-month follow-up (T3), these changes were not statistically significant in the group, time, or interaction effects ($p > 0.40$). The response of IGF-1 to exercise is not uniformly consistent, as evidenced by contradictory findings in the literature (24). Studies with young adults suggest that exercise intensity is a key factor in growth hormone release, including IGF-1, with effects increasing in a dose-response manner (25), which can influence brain structure and function (26). Given our study's focus on HIIT, intensity likely played a central role in the observed tendencies.

Nevertheless, other studies have reported no significant changes or even reductions in IGF-1 levels following similar interventions (27). This variability highlights the complex interplay of factors such as training duration, baseline fitness, and individual response. Still, the evidence suggests that high-intensity exercise triggers metabolic and mechanical stress, which activates key cellular pathways such as the Akt/mTOR cascade—critical for protein synthesis and IGF-1 production (28). The IGF-1/IGF1-BP axis modulates the availability and half-life of IGF-1, affecting cellular proliferation and neuroplasticity (29).

Regarding the residual effect at T3, although IGF-1 concentrations appeared numerically elevated in the HIIT and HIIT + PA groups compared to baseline, the statistical analysis did not confirm significant group differences or interaction effects. These tendencies, while potentially indicative of long-term physiological adaptations, must be interpreted cautiously. Effect sizes and within-group changes can suggest patterns, but without significant omnibus tests, *post hoc* interpretations are limited and should not be overstated.

This aligns with previous literature showing mixed results on IGF-1 responses depending on protocol specifics and individual variability (30–33). While IGF-1 has been widely studied in relation to brain health and neuroplasticity, it is not a clinically validated biomarker of executive function. Therefore, while increases observed in some participants may suggest neurobiological adaptations, the current results do not provide robust statistical evidence to support this as a generalizable effect.

## Changes in executive functions

Recent meta-analyses have investigated the effects of physical exercise on executive functions in young adults (30) showing overall modest effects. While working memory tends to benefit more robustly, inhibitory control shows smaller or null effects (Hedges' $g = 0.16$). These mixed results suggest that the effect of exercise may depend on the specific cognitive domain, intervention characteristics, and participant profile.

In our study, although reductions in interference time (ST-I-T) were observed, these improvements were not specific to the intervention groups, as no group or interaction effects were found. Therefore, the observed improvements may reflect general learning effects, repeated testing, or other non-specific factors, rather than a direct result of the training programs.

In contrast, only the HIIT + PA group showed a significant improvement over time in the number of correct responses, suggesting a possible selective benefit in response accuracy. Nevertheless, the absence of significant between-group differences tempers this conclusion, and prevents us from confidently attributing this change to the training intervention.

This aligns with prior findings indicating that changes in inhibitory control may require longer interventions or be influenced by individual variability, particularly in sedentary women (34, 35). The prefrontal cortex, central to inhibitory control, may not respond immediately to exercise stimuli and may benefit more from sustained engagement or cognitively demanding exercise modalities (33).

Our results show statistically significant improvements over time in the WCST-C and WCST-R variables (Table 5), indicating enhanced cognitive flexibility across the sample. However, since no group × time interaction was found, these improvements cannot be conclusively attributed to the intervention. They may reflect general cognitive engagement, learning effects, or other nonspecific influences over the course of the study.

In WCST-R, although both HIIT and HIIT + PA groups showed increased scores from baseline to T3, the lack of a significant interaction effect ($p = 0.719$) suggests that these gains were not exclusive to the intervention groups, and may have occurred regardless of training.

The only significant between-group effect was observed in WCST-E-P ($p = 0.028$), indicating group-level differences in cognitive rigidity, but not necessarily as a result of the intervention, since neither time nor interaction effects were significant. Interestingly, the control group showed some reduction in perseverative errors over time, which may be influenced by repeated testing rather than specific training-related cognitive adaptation.

These findings differ from previous reports suggesting that structured physical training, particularly HIIT, may influence cognitive flexibility. Meta-analyses such as those by Haverkamp et al. (30) and Hsieh et al. (35) report small or nonsignificant changes in flexibility-related outcomes, supporting our interpretation that these effects may be subtle, delayed, or require complementary interventions such as broader lifestyle changes or cognitive engagement.

Working memory is often one of the most sensitive executive functions to benefit from physical activity in young adults (30, 34). In the present study, the most pronounced improvements

TABLE 5 Differences between different phases and groups in WCST at time T1, T2 and T3.

| Variable | Group | T1 Media (sd) | | T2 Media (sd) | | T3 Media (sd) | | *p* valor time | η² partial | *p* valor group | η² partial | *p* valor group*time | η² partial |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| WCST-C | HIIT | 3.9 | (0.2) | 4.2 | (0.3) | 4.3 | (0.2) | .013* | .69 | .619 | .619 | .719 | .69 |
| | HIIT + PA | 3.8 | (0.2) | 4.1 | (0.2) | 4.6[b] | (0.2) | | | | | | |
| | GC | 3.8 | (0.2) | 4.1 | (0.3) | 4.1 | (0.2) | | | | | | |
| WCST-R | HIIT | 49.3 | (3.6) | 52.5[a] | (3.6) | 53.3[b] | (2.8) | .001* | .201 | .590 | .019 | .497 | .03 |
| | HIIT + PA | 50.9 | (3.7) | 53.1[a] | (3.2) | 54.5[b] | (3.1) | | | | | | |
| | GC | 51.9 | (3.3) | 53.7 | (3.0) | 53.8 | (3.8) | | | | | | |
| WCST-E-P | HIIT | 6.8 | (2.8) | 7.1[c] | (1.0) | 6.3 | (0.8) | .097 | .097 | .028* | .122 | .223 | .223 |
| | HIIT + PA | 6.3 | (2.5) | 5.7 | (1.9) | 5.8 | (1.2) | | | | | | |
| | GC | 7.9[a] | (2.4) | 5.7 | (1.7) | 6.8 | (0.8) | | | | | | |

S, seconds; SD, standard deviation; WCST, Wisconsin card sorting test; WCST-C, completed categories; WCST-R, correct responses; WCST-P-E, perseverative errors.
*Significant differences ($p < 0.05$).
[a]Significant differences between T1 and T2.
[b]Significant differences between T1 and T3.
[c]Significant differences between T2 and T3.

TABLE 6 Differences between different phases and groups in DST at time T1, T2 and T3.

| Variable | Group | T1 Media (sd) | | T2 Media (sd) | | T3 Media (sd) | | *p* valor time | η² partial | *p* valor group | η² partial | p valor group*time | η² partial |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DST-F | HIIT | 5.8 | (1.3) | 6.25 | (0.8) | 6.2 | (1.1) | .565 | | .320 | | .531 | |
| | HIIT + PA | 6.1 | (1.3) | 6.33 | (0.9) | 6.3 | (1.2) | | .01 | | .041 | | .028 |
| | GC | 5.9 | (0.8) | 5.71 | (1.1) | 5.8 | (1.2) | | | | | | |
| | HIIT | 4.5 | (1.2) | 5.4[a] | (1.3) | 5.2[b] | (1.1) | | | | | | |
| DST-B | HIIT + PA | 5.4 | (1.2) | 5.52 | (1.4) | 5.9 | (3.1) | <.001* | .127 | .041* | .109 | .128 | .062 |
| | GC | 4.5 | (1.6) | 4.53 | (1.1) | 5.2[b] | (3.8) | | | | | | |
| DST-T | HIIT | 10.3 | (2.0) | 11.6[a] | (1.5) | 11.5[b] | (1.8) | .001* | | .073 | | .081 | |
| | HIIT + PA | 11.6 | (1.9) | 11.8 | (2.0) | 12.3 | (2.1) | | .113 | | .091 | | .072 |
| | GC | 10.5 | (2.0) | 10.2 | (2.0) | 11.0 | (2.2) | | | | | | |

DST, digit span test; DST-F, forward; DST-B, backward; DST-T, total (forward + backward); s, seconds; SD, standard deviation.
*Significant differences ($P < 0.05$).
[a]Significant differences between T1 and T2.
[b]Significant differences between T1 and T3.

were found in the DST-B, with a highly significant time effect ($p < 0.001$, $\eta^2 = 0.953$), suggesting enhanced capacity for manipulating and recalling information. Nevertheless, the lack of significant group or interaction effects indicates that these improvements were not exclusive to the intervention groups.

In contrast, DST-F did not show significant changes over time ($p = 0.565$), and DST-T, although showing a significant time effect ($p = 0.001$), also lacked significant group-specific effects ($p = 0.081$ for group × time interaction). These findings suggest that all groups, including the control, may have benefited from repeated exposure to the test or from external factors unrelated to the intervention, such as academic engagement or increased mental stimulation during the study period.

Our results partially align with previous literature, where HIIT has shown mixed effects on working memory. While some studies have reported improvements (34), others, like (4), found no significant changes in working memory after similar HIIT protocols in sedentary young women. These inconsistencies may be due to individual differences, intervention duration, cognitive task sensitivity, or external lifestyle factors.

Taken together, although statistically significant changes over time were observed—especially in DST-B—they cannot be confidently attributed to the HIIT or HIIT + PA interventions. Future studies should explore longer intervention periods, more ecologically valid cognitive tasks, and control for confounding lifestyle factors to clarify the relationship between exercise and working memory improvements.

Additionally, although the control group did not receive any intervention, an unexpected increase in IGF-1 levels was observed at T3. This finding, while not aligned with our initial hypothesis, may reflect individual variability or external lifestyle factors not controlled during the study. Future research should further investigate potential causes of such hormonal fluctuations in inactive populations.

Future studies that can administer a measurement of structural change via MRI could generate more information and help us to understand the role of HIIT in all the changes produced, both at the biological, functional and structural level in this population.

We also recognize that many configurations can be found to develop a HIIT training programme, which may have a different effect to those found. However, it is important to note that the study was not designed to uncover such information; instead, it was designed to complement the current literature by demonstrating that HIIT provides improvements in IGF-1 concentration and executive performance, and furthermore, if supplemented with increased daily physical activity, the benefits may be greater.

These findings carry important translational implications. The observed improvements in executive functions, particularly inhibitory control and cognitive flexibility, suggest that HIIT—especially when combined with an increase in daily physical activity—may serve as an effective and time-efficient intervention to support cognitive well-being in sedentary young adults. Given the growing interest in lifestyle-based approaches to mental and cognitive health, these results could help inform physical activity guidelines that incorporate high-intensity interval formats as part of broader strategies aimed at enhancing executive functioning. Further studies are needed to explore how such interventions can be adapted and implemented at the population level.

## Conclusions

In summary, this study provides preliminary evidence that a 12-week HIIT program, particularly when combined with an increase in daily physical activity (HIIT + PA), may contribute to improvements in executive functions—most notably in inhibitory control and cognitive flexibility—in sedentary young women. Although IGF-1 levels and working memory also showed favorable changes over time, these effects could not be definitively attributed to the intervention due to the lack of significant interaction effects. The improvements observed across all groups, including the control group, suggest potential contributions from repeated testing, academic demands, or unmeasured lifestyle factors.

While the overall impact of the interventions was modest, the HIIT + PA condition consistently showed more favorable trends, supporting the notion that combining structured exercise with broader activity-based behavioral changes may enhance cognitive outcomes. These findings underscore the need for future research incorporating longer intervention periods, objective neuroimaging assessments, and tighter control of external variables to better understand the mechanisms underlying exercise-induced cognitive changes. Ultimately, HIIT—when integrated into a physically active lifestyle—emerges as a promising, time-efficient strategy to support cognitive health in young sedentary populations.

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Ethics statement

The studies involving humans were approved by Research Ethics Committee of the Virgen Macarena-Virgen del Rocío University Hospitals (2038-N-20). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

## Author contributions

MJ-R: Writing – original draft, Writing – review & editing. BS: Writing – review & editing. LC: Writing – review & editing.


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The 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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# The effect of a mindful mothering nursing intervention virtual program on mothers with adverse childhood experiences: a randomized controlled trial

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**Background:** Mothers who have experienced adverse childhood experiences often exhibit negative parenting attitudes and behaviors.

**Objectives:** The study we are submitting for consideration is a randomized controlled trial that developed and implemented a mindful mothering nursing intervention virtual program for mothers who have experienced adverse childhood experiences. The primary aim of the study was to evaluate the effectiveness of this intervention.

**Subjects:** The participants of this study comprised 60 mothers who were raising children aged 3 to 7 and had experienced adverse childhood experiences before the age of 18. The participants were randomly assigned to either the experimental group or the control group.

**Tools:** The mindful mothering nursing intervention virtual program was administered to the experimental group over a period of 6 weeks, from June 20 to July 29, 2022. The intervention consisted of weekly sessions, each lasting 120 min, for a total of six sessions. The program covered a range of topics including self-understanding, awareness of adverse childhood experiences, mindfulness based parenting and emotional regulation techniques, understanding children's physical and emotional developmental stages and corresponding parenting attitudes, emotion coaching and child acceptance, strategies for utilizing social support, professional counseling, and self-reflection. To evaluate the effectiveness of the intervention, validated instruments were used to measure adverse childhood experiences, parenting stress, parenting efficacy, mindful parenting attitude, perceived social support, and parenting behavior. Data collection was conducted both prior to the intervention and again 48 h after its completion.

**Result:** In this study, the experimental group showed a statistically significant reduction in mean scores for parenting stress, an increase in parenting efficacy, an improvement in mindful parenting attitude, and more positive parenting behavior compared to the control group. However, there was no statistically significant difference between the two groups in perceived social support ($p < 0.05$).

**Implications:** This underscores the importance of actively implementing parenting nursing interventions for mothers who have experienced adverse childhood experiences to prevent the intergenerational transmission of adverse childhood experiences.

**Conclusion:** Based on the findings of this study, the development of various parenting nursing intervention programs to support mothers with adverse childhood experiences is essential.

**Clinical trial registration:** https://cris.nih.go.kr/cris/search/detailSearch.do?seq=21959&search_page=L, identifier KCT 0007353.

KEYWORDS

adverse, childhood, experiences, mothering, mindfulness, intervention

## Background

According to global statistics from the year 2024, approximately four hundred million children under the age of five, which accounts for about 60 % of that age group, are regularly subjected to psychological violence or physical punishment. Furthermore, it is estimated that around six hundred and fifty million women and girls worldwide have experienced sexual violence before reaching the age of 18, as reported by the United Nations Children's Fund (1). In South Korea, data reported in the year 2023 indicate that the incidence of child abuse reached three hundred sixty-four point one cases per one hundred thousand children, reflecting a high prevalence. Among these cases, approximately 85 % occurred within the family setting. Particularly concerning is the early detection rate of child abuse in South Korea, which stands at only three point six 4 %. This rate is significantly lower than that of other member countries of the OECD, such as the United States at seven point 7 % and Australia at 11 point 7 % (2).

Child abuse is categorized as an adverse childhood experience (ACE), which encompasses traumatic stress resulting from physical, emotional, and sexual abuse, neglect, and exposure to domestic violence among children under the age of 18 (3–6). ACE has been shown to negatively impact interpersonal relationships due to the development of insecure attachment from childhood, and can impair self-regulation abilities (7). Repeated exposure to ACE excessively stimulates the limbic system and disrupts the normal regulation of the hypothalamic–pituitary–adrenal axis, leading to adverse effects on brain development (4–6).

Most critically, individuals who have experienced ACE are at an increased risk of perpetuating abuse as parents (6, 8, 9). This is attributed to the strong correlation between ACE and parenting stress, where the experience of childhood adversity contributes to intergenerational transmission of abuse. The effects are particularly pronounced in mothers who have experienced ACE, as they are more likely to engage in neglectful or punitive parenting, display lower levels of empathy, and exhibit inconsistent caregiving behaviors (10). These parenting practices not only lead to issues such as inattention, hyperactivity, impulsiveness, and aggression in children but also contribute to psychological and emotional problems, including anxiety and depression (5, 6, 9).

Furthermore, these issues extend into the school environment, increasing the likelihood of peer violence and, in adulthood, escalating to dating and domestic violence (6). Recognizing the far-reaching consequences of ACE, the WHO has designated addressing the lifelong physical, mental, and social impairments caused by ACE as a critical public health priority (3).

Structured parenting intervention programs have been shown to positively influence parenting attitudes among mothers who have ACE. These programs assist mothers in improving their emotional regulation, enhancing empathy, and acquiring consistent parenting strategies (5, 6). As a result, punitive parenting behaviors rooted in past experiences of abuse are reduced, enabling mothers to respond more sensitively to their children's needs and to engage in more stable and supportive parenting practices (11). Such improvements play a critical role in preventing the intergenerational transmission of abuse (4–6, 10).

Mindful parenting, in particular, is a parenting approach in which the mother intentionally brings her full attention to the present moment while interacting with her child. This approach involves accepting emotions and thoughts without judgment and responding sensitively to the child's needs and emotional signals (12, 13). Mindful parenting applies the core principles of traditional mindfulness to the parenting context, fostering mothers' emotional regulation and self-awareness (14). It also helps reduce stress and reactive behaviors, thereby promoting more positive and nurturing relationships with their children (12–15). This approach is especially effective for mothers with a history of child abuse, as it supports the restoration of emotional regulation and empathy (6, 16).

Meanwhile, social cognitive theory explains that human behavior is shaped by the dynamic interaction among personal factors, behaviors, and environmental influences. This theoretical framework is valuable for understanding the psychological and behavioral variables related to parenting (17). Parenting stress refers to the emotional strain and sense of burden experienced by parents in the process of raising children. When persistent, parenting stress can lead to increased aggressive or inconsistent negative parenting behaviors. In contrast, parenting efficacy refers to a mother's belief in her ability to parent effectively. Mothers with high parenting efficacy tend to adopt more consistent and stable parenting practices, even in challenging situations (18, 19).

A mindful parenting attitude, defined as a parent's effort to stay emotionally connected with the child while remaining attentive to the present moment, enhances self-awareness and emotional regulation. This, in turn, reduces stress and contributes to improved parenting efficacy (13, 14, 16). Additionally, perceived social support, or a mother's belief that she receives emotional and instrumental assistance from others, acts as a protective buffer during stressful situations and promotes positive parenting behaviors (9, 11). From the perspective of social cognitive theory, parenting stress may have a detrimental effect on parenting behaviors. However, internal and external resources such as parenting efficacy, a mindful attitude, and social support can buffer these negative effects and foster healthier parenting practices (17, 19).

Based on social cognitive theory, the present study aimed to develop and evaluate a parenting intervention program incorporating mindful parenting for mothers with a history of ACE.

## Theoretical background

Women who have experienced adverse events in childhood, such as abuse, neglect, or emotional deprivation, are more likely to encounter psychological and emotional difficulties during the transition to motherhood (5, 8, 10). These early experiences can lead to diminished self-esteem, challenges in forming secure attachments, anxiety related to parenting, and difficulties in emotional regulation (11). Such issues may disrupt healthy interactions with their children and contribute to the development of maladaptive parenting practices (6, 8). In particular, negative parenting experiences from the past may be unconsciously reenacted or lead to excessive efforts to avoid such behaviors, resulting in confusion and stress regarding the maternal role (5, 8, 10). These unresolved emotional wounds can distort perceptions of current parenting situations and hinder the establishment of a coherent maternal identity (18). Therefore, mothers with such histories require professional psychosocial support and therapeutic intervention, both of which are essential for the restoration of healthy maternal functioning and for the developmental well-being of their children (6, 11).

Parenting intervention programs grounded in social cognitive theory have evolved to address broader issues related to generalizability and mechanisms of behavioral change (12, 15). These programs are increasingly examined for their potential to explain the mechanisms through which positive changes in parenting attitudes and behaviors occur among mothers with adverse childhood experiences (4, 5, 8, 10). According to social cognitive theory, parenting behaviors can be shaped through direct and indirect modeling, whereby exposure to positive parenting examples leads to the adoption of healthier practices (17). This modeling process can take various forms and includes reinforcement, allowing learned behaviors to be maintained across different contexts and over time (19). As such, interventions targeting the parenting attitudes and behaviors of mothers with early adverse experiences have focused on improving parenting quality as a means of preventing intergenerational transmission of abuse (5, 6, 11).

Notable examples of evidence-based parenting programs include the ACT raising safe kids program, the Triple P positive parenting program, and the incredible years program (20). The ACT program, developed by the American Psychological Association, is designed to prevent child maltreatment and promote positive parenting skills among parents and caregivers of children from birth to age 10. It addresses topics such as nonviolent discipline, child development, anger management, conflict resolution without violence, the impact of violent media on children, and strategies for child protection (21). The Triple P program provides parents with tailored knowledge and skills to build confidence and promote positive parenting practices. Similarly, the Incredible Years program, designed for parents of children aged 4 to 12, helps prevent and manage behavioral problems in children effectively (20, 21).

Mindfulness is defined as the intentional, nonjudgmental awareness of the present moment. It fosters self-acceptance and reduces internal conflict through cognitive awareness, thereby positively influencing parenting attitudes. Mindfulness-based parenting has been shown to improve consistency and flexibility in parenting approaches and to reduce automatic negative responses toward children. Core components of mindful parenting include attentive listening, nonjudgmental acceptance of both self and child, emotional awareness, self-regulation, and self-compassion (12, 14, 16). Previous research has demonstrated that mindful parenting effectively reduces parenting stress and enhances parent–child relationships (16).

The distinction between social learning and mindfulness lies more in their conceptual foundations than in empirical practice. However, the potential integration of these models has been highlighted in meta-analyses of mindful parenting interventions. These analyses have shown that the most favorable outcomes in parenting behavior are associated with studies that employed specific behavioral techniques, suggesting that the mechanisms of change may reside more in applied methods than in conceptual frameworks alone (22, 23).

In this study, we took a novel approach by developing the mindful mothering nursing intervention virtual program (MMNI), which uniquely integrates social cognitive theory with a mindful parenting framework. This integration was purposefully designed to offer a more comprehensive and theoretically grounded strategy for supporting mothers with a history of ACE, thereby addressing a critical gap left by previous intervention studies.

## The study objectives

This study aimed to develop the MMNI for Korean mothers with ACE and evaluate its effectiveness using a randomized control-group pretest-posttest design. To develop the program, a comprehensive review of previous studies on child maltreatment and parenting programs was conducted, analyzing their findings. Based on this review, in-depth interviews were conducted with 10 mothers who had experienced ACE to assess their needs for the program. Subsequently, recent parenting programs implemented overseas were analyzed, with reference to evidence-based resources such as the California evidence-based clearinghouse for child welfare (CEBC) and national registry of evidence-based programs and practices (NREPP), which aligned most closely with the objectives of this study.

To ensure the validity of the topics and content in MMNI of this study, expert consultations were conducted. The final program was structured as a virtual intervention consisting of six sessions, totaling 12 h. Each session lasted 120 min and was facilitated by the researcher. Additionally, mindful meditation exercises and an open chatroom were provided to allow participants to engage with the program beyond scheduled sessions, ensuring accessibility regardless of time and location.

To evaluate the intervention effects of the MMNI, the study formulated the following hypotheses:

> *H1*: The experimental group will experience a greater reduction in parenting stress compared to the control group after program participation.
>
> *H2*: The experimental group will show a greater increase in parenting efficacy compared to the control group after program participation.
>
> *H3*: The experimental group will demonstrate a greater improvement in mindful parenting attitudes compared to the control group after program participation.

> *H4*: The experimental group will perceive a greater increase in perceived social support compared to the control group after program participation.
>
> *H5*: The experimental group will exhibit a greater increase in positive parenting behaviors compared to the control group after program participation.

# Methodology and materials

## Study design

This study employed a randomized control-group pretest-posttest design to develop and evaluate the effectiveness of the MMNI for Korean mothers with ACE. The conceptual framework an flowchart of study are illustrated in Figures 1, 2.

## Setting and participants

The participants were mothers residing in two cities in South Korea who were raising children aged 3 to 7 years and had experienced ACE before the age of 18. Mothers with physical or psychological difficulties, communication disorders, or those currently taking anxiolytics or sedatives were excluded from the study.

To recruit participants, advertisements were posted in local kindergartens and social network communities within the Seoul and Gyeonggi, South Korea. Mothers who expressed interest in participating were provided with a detailed explanation of the study's objectives and procedures. Those who voluntarily provided written informed consent were then asked to complete a screening survey to determine their ACE history. The ACE questionnaire is generally interpreted as follows: scores of 3 or lower indicate relatively low risk; scores of 4 or higher are associated with a significantly increased risk of mental health issues, physical health problems, and behavioral difficulties; and scores of 6 or above are considered indicative of a high-risk group for outcomes such as suicide attempts, substance abuse, and chronic illnesses (24). In this study, participants with ACE scores of 4 or higher were included. Only those who met the eligibility criteria were randomly assigned to either the experimental or control group. Participants who were currently taking psychiatric medication due to past ACE were excluded from this study. However, it was clearly explained to all participants that they could withdraw from the study at any time if they experienced physical or psychological discomfort related to past ACE during the course of the intervention. In such cases, they would be referred to a licensed counselor or medical professional for appropriate support.

## Sample size

The required sample size was determined using G*Power 3.1.9.2 software. Based on previous studies on parenting intervention programs for child maltreatment prevention (25), the sample size was calculated with a significance level ($\alpha$) of 0.05, statistical power (1-$\beta$) of 0.80, and an effect size of 0.8. The results indicated that 26 participants per group were required, totaling 52 participants. Considering potential attrition, the sample size was increased to 60 participants (30 in the experimental group and 30 in the control group).

## Random assignment

A total of 60 mothers who met the eligibility criteria were assigned a unique identification number based on the order of their study registration. The plan was to allocate 30 participants to the experimental group and 30 to the control group. To ensure randomization, a computerized randomization tool was used to generate randomized allocation numbers, which were then used to automatically assign participants to either the experimental or control group. Before the intervention, all 60 participants completed the pretest survey. However, five participants in the experimental group withdrew from the study

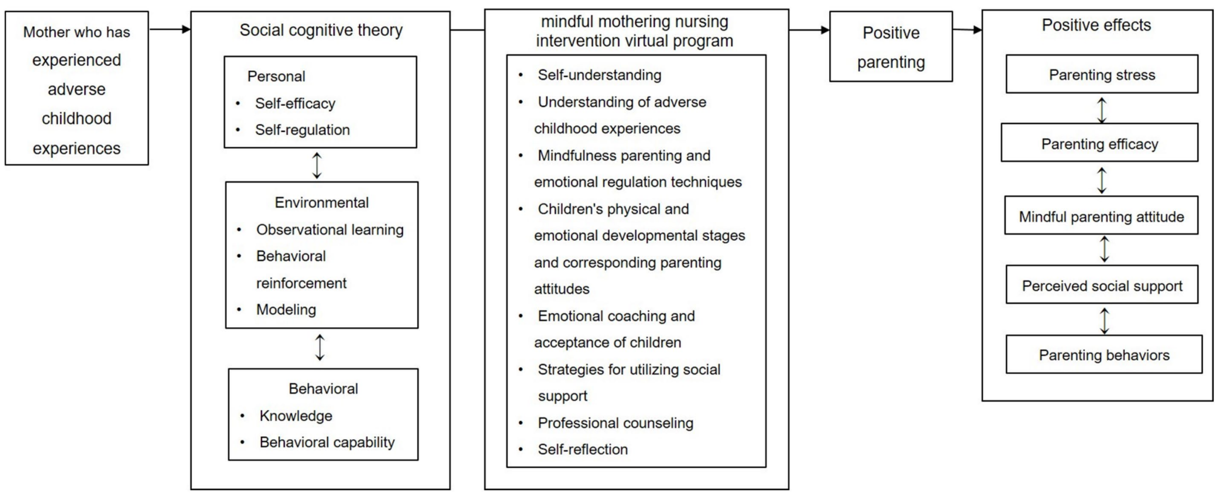


FIGURE 1
Conceptual framework of this study.

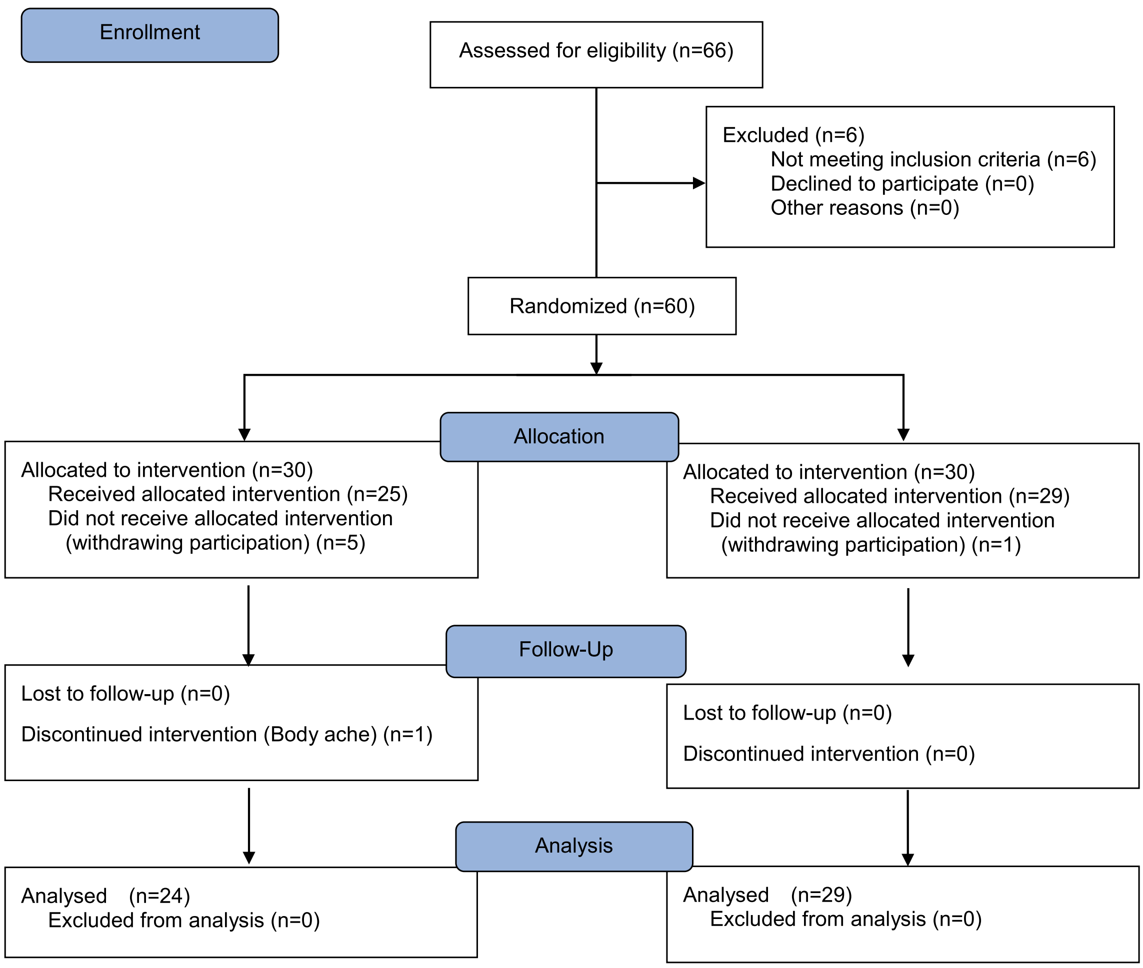


FIGURE 2
Consort flow diagram for individual randomized controlled trial of the intervention.

due to concerns about potential identification by others, and one participant in the control group was lost to follow-up. As a result, the final sample consisted of 25 participants in the experimental group and 29 in the control group. To maintain single blinding in this randomized controlled trial, participants were not informed of the specific details of the intervention program and were unaware of whether they had been assigned to the experimental or control group.

## Measurements

### Adverse childhood experiences

ACE were assessed using the Korean-translated version of the ACE questionnaire for adults – identified, originally developed by Felitti et al. (24). This instrument comprises 10 items, each requiring a binary response ('Yes' or 'No'). A higher number of 'Yes' responses indicates a greater severity of ACE. In this study, the reliability of the scale was Cronbach's α = 0.87.

### Parenting stress

Parenting stress was measured using the Korean-translated version of the parenting stress index short form (PSI-4-SF) and translated by Jeong et al. (26). This instrument consists of 36 items, categorized into three subscales: Parental distress (12 items), dysfunctional parent–child interaction (12 items), and difficult child (12 items). Each item is rated on a 5-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree), with higher scores indicating greater parenting stress. The reliability of the instrument in this study was Cronbach's α = 0.95 for both pretest and posttest.

### Parenting efficacy

Parenting efficacy was assessed using the Korean-translated version of the tool to measure parenting self-efficacy. The translation was conducted following the guidelines provided by the WHO (27), and its content validity was verified through expert consultation (three nursing professors, two pediatricians, one pediatric nurse specialist, and one psychiatric nurse specialist). The instrument consists of 48 items across eight subdomains and each item is rated on an 11-point Likert scale from 0 (strongly disagree) to 10 (strongly agree), with higher scores indicating greater parenting efficacy. The reliability of this instrument in this study was Cronbach's α = 0.97 for both pretest and posttest.

### Mindful parenting attitude

Mindful parenting attitude was measured using the Korean-translated version of the interpersonal mindfulness in parenting scale, translated by Kim et al. (13). This instrument consists of 18 items and each item is rated on a 5-point Likert scale from 1 (strongly disagree) to 5 (strongly agree), with higher scores indicating a higher level of mindful parenting. The overall reliability of the instrument in this study was Cronbach's $\alpha = 0.86$ (pretest) and Cronbach's $\alpha = 0.87$ (posttest).

### Perceived social support

Perceived social support was measured using the instrument developed by Park (28). This instrument consists of 25 items and each item is rated on a 5-point Likert scale from 1 (strongly disagree) to 5 (strongly agree), with higher scores indicating a higher level of perceived social support. The reliability of the instrument in this study was Cronbach's $\alpha = 0.97$ (pretest) and Cronbach's $\alpha = 0.98$ (posttest).

### Parenting behavior

Parenting behavior was assessed using the Korean-translated version of the instrument developed by Silva (29). This instrument consists of 30 items, and the subdomains of parenting style and parental behavior are rated on a 5-point Likert scale, and the media discipline item is rated on a 4-point Likert scale. A higher score indicates more positive parenting behavior. The reliability of the instrument in this study was Cronbach's $\alpha = 0.89$ for both pretest and posttest.

# Data collection and analysis

## Pretest

The pretest was conducted from June 13 to June 19, 2022, with 60 participants who agreed to participate in the study. Prior to the pretest, an orientation session was held from June 7 to June 10, 2022. The pretest was conducted online via a questionnaire covering demographic characteristics, parenting stress, parenting efficacy, mindful parenting attitude, perceived social support, and parenting behavior.

## Experimental treatment

Following the orientation, the MMNI, designed for mothers with children aged 3 to 7, was conducted via Zoom. Participants assigned to the experimental group were provided with an individual URL to access the program, while the control group received a parenting education manual from the Korea healthy family promotion institute via text message. The MMNI was administered to the experimental group over a period of 6 weeks, from June 20 to July 29, 2022. The intervention consisted of weekly sessions, each lasting 120 min, for a total of six sessions. In the first week, participants engaged in a life graph drawing activity designed to promote self-understanding and awareness of their ACE. In the second week, the focus was on acquiring knowledge related to stress, event-related trauma, and developmental trauma stemming from childhood ACE. Participants also practiced breathing meditation techniques aimed at regulating internalized negative emotions. During the third week, participants explored the stages of physical and emotional development in children and learned emotion regulation strategies modeled to enhance self-efficacy and foster a more accepting parenting attitude through self-regulation. The fourth week emphasized the use of social support strategies, including emotional coaching through professional counseling. Participants were also guided through self-reflection exercises. In the fifth week, role-playing activities were conducted based on various scenarios, including loving-kindness meditation and communication skills with children. The sixth week provided an opportunity for participants to review their relationships with their children, reflect on broader social relationships with family and friends, and receive information about professional support systems available within the community. Throughout the 6-week program, participants received regular text messages encouraging the practice of walking meditation and breathing exercises for emotional self-regulation. They were asked to respond regarding their participation and, before sleep or during parent–child interactions, to express their emotions metaphorically using colors and report them to the researcher. In addition, an alert system was made available throughout the intervention period for participants to request support when needed, and referrals to professional services were arranged as necessary.

The content provided to the control group consisted of general educational materials commonly offered to mothers and was entirely different from the intervention content received by the experimental group. For example, the control group materials addressed topics such as normal physical development in children, vaccination schedules and procedures, safety management, hygiene practices, and nutritional care. One participant in the experimental group withdrew from the study before completing the program; accordingly, all pre-intervention survey data from this participant were discarded. As the program was conducted virtually, the URL for the intervention was provided exclusively to participants in the experimental group, making face-to-face interaction or contact information exchange between the experimental and control groups impossible. Participants in the experimental group were granted unlimited access to mindfulness resources, including breathing and walking meditation exercises. Additionally, they were encouraged to form a supportive community by participating in an open group chat with other members of the experimental group.

## Posttest

The posttest was conducted 48 h after the experimental treatment concluded, using the same questionnaire as the pretest. The posttest period was from August 1 to August 5, 2022, with 24 participants from the experimental group and 29 participants from the control group completing the survey. In addition, 7 days after the completion of the post-intervention survey, an informational email regarding the program provided to the experimental group was sent to the control group. For those who expressed interest, the same program was offered 1 month after its completion in the experimental group.

## Researcher preparation

To ensure the necessary qualifications for conducting this study, the researcher undertook several professional development efforts to acquire relevant knowledge and skills. The researcher completed *the*

*ACT raising safe kids facilitator training workshop,* a parenting program developed by the American Psychological Association, which provided the foundation for fulfilling both counseling and facilitation roles during the mindfulness-based intervention. Additionally, the researcher completed a 40-h m*indfulness-based stress reduction* course, thereby gaining the competency to lead mindfulness meditation practices and serve as an educator for mothers with adverse childhood experiences. Furthermore, the researcher received training in focus group interview methodology, which enabled the use of in-depth interviewing techniques to elicit participants' deeper insights and experiences.

## Data analysis

Data analysis was conducted using SPSS 26.0 (IBM Corp., Armonk, NY, USA). Descriptive statistics were used to analyze participants' demographic characteristics. Baseline equivalence between the experimental and control groups was tested using independent t-tests for continuous variables and Chi-square tests or Fisher's exact tests for categorical variables. Skewness and kurtosis were assessed to check the normality of key variables. Pretest-posttest differences in parenting stress, parenting efficacy, mindful parenting attitude, perceived social support, and parenting behavior within each group were analyzed using paired sample t-tests. Differences in post-intervention mean scores between the experimental and control groups were analyzed using independent t-tests. Also, The effect size of the program was calculated using Cohen's *d*, which is obtained by dividing the difference in means between the two groups by the pooled standard deviation. According to Cohen's criteria, a *d* value of 0.2 or less was interpreted as a small effect size, 0.5 as a medium effect size, and 0.8 or greater as a large effect size (30).

## Ethical considerations

This study was approved by the institutional review board of the university to which the researcher is affiliated on April 20, 2022 (No: 1041078-202112-HR-345-01), and received approval as a registered clinical research institution from the national institutes of health and the Korea disease control and prevention on May 3, 2022. (No: KCT 0007353)[1].

Prior to the study, participants were fully informed about the purpose of the research, the confidentiality of the data, and the data disposal procedures after the conclusion of the study. Consent for voluntary participation was obtained. Additionally, participants were informed that they could withdraw from the study at any time without any negative consequences. Furthermore, all measurement tools used in this study were utilized only after receiving permission from the original authors and the translators.

1 https://cris.nih.go.kr/cris/search/detailSearch.do?seq=21959&search_page=L

# Results

## General characteristics and homogeneity verification of participants

The average age of the participants was 34.63 ± 7.77 years in the experimental group and 34.14 ± 7.24 years in the control group. Regarding marital status, 23 participants (95.8%) in the experimental group and 27 participants (93.1%) in the control group were married. In terms of education level, the highest proportion of participants in both groups were university graduates, accounting for 66.7% in the experimental group and 72.4% in the control group. Additionally, the most common number of children aged 3 to 7 years was two, reported by 58.3% of the experimental group and 51.7% of the control group.

There were no statistically significant differences between the two groups in terms of average age, religion, marital status, education level, employment status, number of children, average monthly income, confirming the pre-experimental homogeneity of the groups (Table 1).

## Homogeneity test of outcome variables before the intervention

There were no statistically significant differences between the experimental and control groups in the pre-experimental mean scores for parenting stress ($t = 0.07$, $p = 0.291$), parenting efficacy ($t = -0.90$, $p = 0.372$), mindful parenting attitude ($t = -0.26$, $p = 0.799$), perceived social support ($t = -0.22$, $p = 0.829$), or parenting behavior ($t = -0.84$, $p = 0.404$). These results confirm the pre-experimental homogeneity of the two groups (Table 2).

## Hypothesis testing

The results of the hypothesis testing are presented in Table 3.

After the experimental treatment, the mean pre-post score for parenting stress decreased in the experimental group (−0.83 ± 0.55), whereas it slightly increased in the control group (0.02 ± 0.12). This supports Hypothesis 1 ($t = -7.40$, $p = <0.001$).

The mean pre-post score for parenting efficacy increased in both the experimental group (1.16 ± 1.15) and the control group (0.06 ± 0.46). However, the difference between the two groups was statistically significant, supporting Hypothesis 2 ($t = 4.41$, $p = <0.001$).

Similarly, the mean pre-post score for mindful parenting attitude increased in both the experimental group (0.43 ± 0.60) and the control group (0.05 ± 0.29), with a statistically significant difference between the two groups. This supports Hypothesis 3 ($t = 2.86$, $p = 0.007$).

Hypothesis 4, which proposed that perceived social support would increase more in the experimental group than in the control group, was rejected due to the absence of a statistically significant difference between the two groups ($t = 1.87$, $p = 0.072$).

Regarding positive parenting behavior, the mean pre-post score increased in the experimental group (0.36 ± 0.48) but decreased in the control group (−0.08 ± 0.23). This supports Hypothesis 5 ($t = 4.10$, $p < 0.001$).

TABLE 1 Baseline characteristics and homogeneity testing of participants.

(*N*=53)

| Variables | Categories | Exp. Group (*N* = 24) | Cont. Group (*N* = 29) | Total (*N* = 53) | $\chi^2$ / *t* | *p* |
|---|---|---|---|---|---|---|
| | | *N* (%) or Mean±SD | M (%) or Mean±SD | M (%) or Mean±SD | | |
| Age (years) | | 34.63 ± 7.77 | 34.14 ± 7.24 | 34.36 ± 7.41 | 0.24 | 0.814 |
| Religion | Christian | 8 (33.3) | 6 (20.7) | 14 (26.4) | 2.25 | 0.523 |
| | Buddhism | 3 (12.5) | 2 (6.9) | 5 (9.4) | | |
| | Catholic | 2 (8.3) | 5 (17.2) | 7 (13.2) | | |
| | No Religion | 11 (45.8) | 16 (55.2) | 27 (50.9) | | |
| Marital status | Married | 23 (95.8) | 27 (93.1) | 50 (94.3) | 0.18 | 0.669 |
| | Unmarried | 1 (4.2) | 2 (6.9) | 3 (5.7) | | |
| Education level | High School | 6 (25.0) | 6 (20.7) | 12 (22.6) | 0.21 | 0.902 |
| | College | 16 (66.7) | 21 (72.4) | 37 (69.8) | | |
| | Graduate School | 2 (8.3) | 2 (6.9) | 4 (7.5) | | |
| Occupation | No | 18 (75.0) | 21 (72.4) | 39 (73.6) | 6.15 | 0.631 |
| | Yes | 6 (25.0) | 8 (27.6) | 14 (26.4) | | |
| Number of children | 1 | 7 (29.2) | 11 (37.9) | 18 (34.0) | 0.46 | 0.796 |
| | 2 | 14 (58.3) | 15 (51.7) | 29 (54.7) | | |
| | 3 | 3 (12.5) | 3 (10.3) | 6 (11.3) | | |
| Monthly income (million won) | | 4.96 ± 2.21 | 5.42 ± 1.82 | 5.21 ± 2.00 | 0.84 | 0.407 |

SD, Standard deviation; ACEs, Adverse childhood experience; Exp, Experimental; Cont, Control.

TABLE 2 Homogeneity test of outcome variables before the intervention.

(*N*=53)

| Variables | Exp. Group (*N* = 24) | Cont. Group (*N* = 29) | *t* | *p* |
|---|---|---|---|---|
| | Mean±SD | Mean±SD | | |
| Parenting stress | 3.08 ± 0.74 | 2.88 ± 0.67 | 1.07 | 0.291 |
| Parenting efficacy | 6.29 ± 1.64 | 6.69 ± 1.58 | −0.90 | 0.372 |
| Mindfulness parenting attitude | 2.89 ± 0.65 | 2.94 ± 0.67 | −0.26 | 0.799 |
| Perceived social support | 3.31 ± 0.89 | 3.36 ± 0.92 | −0.22 | 0.829 |
| Parenting behavior | 3.13 ± 0.55 | 3.26 ± 0.51 | −0.84 | 0.404 |

SD, Standard deviation; Exp, Experimental; Cont, Control.

## Discussion

This study was conducted to develop an MMNI based on social cognitive theory for mothers with ACE, and to verify its effectiveness. In this regard, the results will be discussed based on the hypotheses proposed in this study.

As a result of the study, Hypothesis 1 was supported, as the parenting stress of the experimental group participating in the MMNI was statistically significantly reduced compared to the control group. Parenting stress is experienced by all parents in general; however, for mothers who have experienced ACE, the psychological pain formed since childhood negatively impacts parenting behaviors, which in turn exacerbates parenting stress (4, 8, 10). In particular, these mothers experience difficulty in regulating their emotions in the context of intensified parenting stress, which can lead to child abuse (11, 18). Furthermore, through coping mechanisms such as neglect, harsh discipline, inconsistent parenting, and lack of empathy, ACE can contribute to an intergenerational cycle of adversity (4, 11). Given the detrimental effects of ACE on the mental health of both mothers and their children, addressing trauma-based stress is a critical public health priority (29). Parenting intervention programs that target the mental health of mothers with ACE can lead to positive improvements in parenting outcomes. A meta-analysis of group-based interventions demonstrated that such programs not only reduce stress among mothers with ACE but also have beneficial effects on parenting behaviors and perceived parenting efficacy (6). The MMNI in this study also incorporated self-understanding as the first step in the intervention, allowing participants to write their life graphs and share experiences to help them regulate their emotions objectively. Additionally, the program

TABLE 3 Comparison of parenting-related outcomes before and after the intervention.

(*N*=53)

| Variables | Group | Pre Mean±SD | Post Mean±SD | Difference Mean±SD | *t* | *p* | Cohen's *d* |
|---|---|---|---|---|---|---|---|
| Parenting stress | Exp. | 3.08 ± 0.74 | 2.25 ± 0.49 | −0.83 ± 0.55 | −7.36 | < 0.001 | 2.14 |
| | Cont. | 2.88 ± 0.67 | 2.90 ± 0.64 | 0.02 ± 0.12 | 0.92 | 0.365 | |
| Parenting efficacy | Exp. | 6.29 ± 1.64 | 7.45 ± 1.16 | 1.16 ± 1.15 | 4.92 | < 0.001 | 1.26 |
| | Cont. | 6.69 ± 1.58 | 6.74 ± 1.47 | 0.06 ± 0.46 | 0.65 | 0.522 | |
| Mindful parenting attitude | Exp. | 2.89 ± 0.65 | 3.32 ± 0.66 | 0.43 ± 0.60 | 3.55 | 0.002 | 0.81 |
| | Cont. | 2.94 ± 0.67 | 2.99 ± 0.62 | 0.05 ± 0.29 | 1.00 | 0.327 | |
| Perceived social support | Exp. | 3.31 ± 0.89 | 3.75 ± 1.02 | 0.44 ± 0.84 | 2.56 | 0.018 | 0.53 |
| | Cont. | 3.36 ± 0.92 | 3.46 ± 0.85 | 0.10 ± 0.34 | 1.56 | 0.130 | |
| Parenting behavior | Exp. | 3.13 ± 0.55 | 3.49 ± 0.53 | 0.36 ± 0.48 | 3.66 | 0.001 | 1.17 |
| | Cont. | 3.26 ± 0.51 | 3.18 ± 0.52 | −0.08 ± 0.23 | −1.87 | 0.072 | |

SD, Standard deviation; Exp, Experimental; Cont, Control.

included techniques such as breathing meditation, loving-kindness meditation, and walking meditation to help participants regulate intense emotions. This can be seen as an intervention strategy emphasized in mindfulness-based parenting, where mothers are encouraged to shift their attention from various stresses in the parenting process toward themselves, and to accept their parenting environment as it is (7, 12). This self-regulation process interacts with self-efficacy and positively influences the reduction of parenting stress (9, 14).

Self-efficacy is also closely related to parenting efficacy (15–17), and in this study, the experimental group's parenting efficacy showed a statistically significant difference compared to the control group, supporting Hypothesis 2. Parenting efficacy refers to a parent's belief in their ability to effectively parent their child. Parents with high parenting efficacy tend to solve problems positively when unexpected difficulties arise in the parenting process (22). Moreover, parents with high parenting efficacy exhibit consistent parenting attitudes, which are crucial for the child's physical development and emotional stability (25). In particular, the parenting efficacy of mothers with ACE provides the possibility of breaking the intergenerational transmission of ACE by helping them break free from negative past experiences (8, 11). Previous research has suggested child emotion coaching as one of the effective interventions to strengthen parenting efficacy, particularly for mothers with ACE (31). Child emotion coaching is a parenting method that helps mothers understand, empathize with, and appropriately express their child's emotions (25). It not only addresses the mother's emotions but also provides correct knowledge about child development at different stages and behaviors, as well as how to respect the child's emotions (5, 10). Through this process, mothers are equipped with the ability to effectively understand and raise their children, which helps them gain confidence in parenting (4, 7). The MMNI in this study also included child emotion coaching, where role-playing based on various scenarios was used to help mothers understand and empathize with their children. This applied the behavioral determinants (knowledge, behavioral capability) proposed in social cognitive theory, strengthening non-violent parenting behaviors and training mothers to look into their children's emotions (23, 25). Although ACE are often associated with an intergenerational cycle of adversity, many mothers demonstrate remarkable resilience in the face of such experiences. This resilience is frequently rooted in a strong desire to improve their children's lives and a sense of parenting efficacy that motivates them to reconsider and transform traditional caregiving practices. These findings highlight the multidimensional and dynamic nature of intergenerational ACE transmission, underscoring the need for accessible, trauma-informed parenting interventions that build upon mothers' inherent wisdom and strengths (22, 32).

In the results of this study, the experimental group's mindfulness parenting attitude was statistically significantly higher than the control group, supporting Hypothesis 3. Mindfulness parenting attitude refers to the attitude of a parent who regulates emotions such as anger and frustration, and objectifies the current situation to accept the child's emotions and behaviors during parenting (22). This interacts with parenting stress and parenting efficacy and is a crucial factor for mothers with ACE to practice open acceptance in their relationship with their children (12, 17). From the perspective of social cognitive theory, mindfulness parenting attitude strengthens mothers' cognitive and emotional self-regulation abilities, creating a modeling process for parenting happiness (12, 33). To achieve this, it is important to provide correct knowledge about the difference between punishment and discipline, and to offer solutions to resolve mother–child conflicts (16, 20). Therefore, in the MMNI of this study, case studies of mother–child conflicts and their coping strategies were shared with experts, helping participants shift fixed and repetitive parenting attitudes. This intervention process provided theoretical grounds for helping mothers create a stable emotional environment with their children and perform healthy maternal roles by guiding them toward more positive parenting attitudes. It is important to emphasize the expansion of parenting education programs that foster cooperation and empathy in the parent–child relationship, thereby enhancing parenting competence and emotional regulation.

It is necessary to integrate more explicitly the influence of the social environment and the importance of observational learning, which are both core elements of social cognitive theory, into this study. The MMNI was implemented in a group-based format, and the interactions among participants naturally facilitated the development of social support and the modeling of behaviors. This group setting offered participants opportunities to observe and learn from each other's parenting attitudes and behaviors, which is consistent with the concept of observational learning as outlined in social cognitive theory (19, 23). However, Hypothesis 4, regarding the difference in perceived social support between the experimental and control groups, was rejected. Perceived social support plays a critical role as an environmental factor in enhancing emotional stability and resilience among mothers with ACE (23, 31). Moreover, Perceived social support provides coping strategies in stressful situations and helps overcome difficulties arising in the parenting process (9). Social cognitive theory also suggests that modeling provided within socially supportive environments is essential for positively transforming past experiences learned through exposure to ACE (9, 17). In the MMNI of this study, information about social resource institutions available in the current Korean community was provided, and participants were guided on how to utilize them. Currently, in Korea, various services such as child abuse prevention, early support pilot programs, family function enhancement programs, parenting coaching, and care, medical, and living support services are available. However, the awareness of these services is still low, and access to them is not easy across different residential areas, which limits their utilization (34). Moreover, social support tends to develop and strengthen over time, rather than through short-term interventions; thus, the duration of the intervention in this study may not have been sufficient to capture its full effect. Additionally, the quality and nature of social support are heavily influenced by individuals' subjective perceptions, and it is possible that the MMNI program was not perceived by participants as a meaningful source of support. Furthermore, if participants were already receiving a certain level of support from family members, the additional impact of the MMNI intervention may have been limited (35). Therefore, future interventions should ensure an adequate duration and incorporate components that address the sub dimensions of social support in both design and evaluation.

Finally, Hypothesis 5, which posited that the parenting behavior of the experimental group would significantly increase compared to the control group, was supported by the results. Parenting behavior refers to the various actions and attitudes parents exhibit to help their children grow and develop, and is correlated with parenting stress, parenting efficacy, mindfulness parenting attitude, and perceived social support (5, 8, 22). Mothers with ACE are more likely to overprotect or, conversely, be avoidant in their parenting, which can lead to emotional behavioral problems in their children, delayed physical growth, social deficits, excessive reliance on smartphones, or behavioral issues (5). In particular, parenting behavior is influenced by personal experiences, learning, and cultural factors. Korea, being a collectivist culture, places importance on obedience to authority and social hierarchy, and as a result, it is often considered inappropriate for mothers to play with their children in non-peer group settings (36). Additionally, due to the emphasis on social harmony in Korean culture, self-expressive behaviors like emotional expression are often suppressed by social norms, and there is a prevalent belief that education is a means of social mobility and success, which emphasizes academic achievement and peer competition (36). These factors influence mothers' negative parenting behaviors and can further exacerbate negative behaviors in mothers with ACE. Therefore, it is essential to understand the influence of cultural factors on mothers' parenting behaviors and their reflections on these behaviors (37). The MMNI in this study provided mothers with ACE the opportunity to reflect on their daily routines, emotions, and parenting behaviors, and to share their experiences through a chat room via smartphone, offering them a chance to evaluate their parenting behaviors. This process likely contributed to the significant differences observed in parenting behavior outcomes in this study, supporting the notion that self-reflection influences parenting behavior (25, 31, 32). From the perspective of social cognitive theory, environmental factors play a crucial role in understanding the parenting behaviors of mothers with ACE, as the theory posits that environment is one of the key determinants that both influences and is influenced by individual cognition and behavior (5, 10, 17). Mothers who have experienced ACE often grow up observing negative parenting models, which can adversely affect the way they parent their own children (38). Therefore, the presence of positive social support systems in adulthood, including support from family members, interactions with other parents who are peers, and participation in professional intervention programs, serves as a critical environmental resource that enables these mothers to learn and implement new parenting behaviors (29). In this context, the MMNI provided opportunities for observational learning, allowing mothers with ACE to encounter positive parenting models that differ from those they were exposed to in childhood, and to internalize and apply these new behaviors. Thus, the program may have functioned as a key facilitating factor in promoting positive parenting practices among mothers with ACE.

## Implications

This study emphasizes the significant importance of the MMNI in transforming negative parenting practices into positive ones for mothers who have experienced ACE. Our findings highlight the urgent need for nursing to screen mothers with ACE in clinical and community settings, to recognize and empathize with their past experiences. Furthermore, by investing in the development of nursing intervention programs that transform their negative parenting behaviors, a more compassionate approach to care can be fostered. In addition, raising awareness about ACE and creating a supportive environment for women across the lifespan will contribute to the physical and mental health of mothers. Cultural differences significantly influence individuals' perceptions and behaviors; therefore, mindfulness-based intervention programs should be adapted to reflect the values and contextual factors of each culture. For mothers in particular, variations in parenting practices, social roles, and sources of stress necessitate culturally sensitive program designs. Such tailored approaches are likely to enhance the effectiveness, acceptance, and sustainability of the interventions. Also, this study's findings may offer insights into how MMNI can be generalized beyond Korean mothers with ACE to more diverse populations globally. Additionally, the results could be translated into educational modules for healthcare professionals working with individuals who have experienced childhood trauma.

## Limitations

This study has limitations in generalizing the results to all mothers with ACE, as it was conducted using a randomized controlled trial with mothers residing in Seoul and Gyeonggi Province, South Korea. Additionally, considering the COVID-19 pandemic, the virtual intervention program developed and applied in this study may have introduced uncontrollable variables. Therefore, further research is needed to investigate the long-term effects of MMNI. Although this study demonstrated positive short-term outcomes, future research should investigate whether these effects lead to sustained changes in parenting behaviors and child development over time. For example, follow-up studies using repeated measures ANOVA or ANCOVA could be conducted to examine long-term effects. This study relies on self-reported data, passive delivery of information, brief intervention duration, and lack of interpersonal engagement, which may be affected by cultural desirability bias or subjective interpretation, leading to inaccuracies. Future research could integrate additional objective measurements or observational data to strengthen the validity of the results.

## Conclusion

This study aimed to develop and apply the MMNI for mothers with ACE in Korea and to verify its effectiveness through an RCT. The results showed significant differences in parenting stress, parenting efficacy, mindfulness parenting attitude, and parenting behavior in the experimental group, supporting the hypotheses. However, perceived social support did not show significant differences. This study contributes scientifically by providing evidence that a structured, MMNI can enhance parenting attitudes, increase parenting efficacy, and promote mindfulness parenting behavior among mothers with ACE. The program facilitated improved emotional regulation and reflective caregiving behaviors, supporting healthier mother–child interactions. It offers a trauma-informed framework for parenting support, addressing intergenerational impacts of ACE.

## Author's note

This article is a revision of the first author's doctoral dissertation from Chung-Ang University.

## Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

## Ethics statement

The studies involving humans were approved by Chung-Ang University IRB (1041078-202112-HR-345-01). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

## Author contributions

EC: Methodology, Formal analysis, Data curation, Software, Investigation, Writing – review & editing, Conceptualization, Resources, Writing – original draft. GS: Data curation, Project administration, Validation, Supervision, Formal analysis, Methodology, Visualization, Conceptualization, Writing – original draft, Writing – review & editing.

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## Conflict of interest

The 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.

## Generative AI statement

The authors declare that no Gen AI was used in the creation of this manuscript.

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# Gender stereotypes and female exercise behavior: mediating roles of psychological needs and negative emotions

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**Introduction:** Integrating Expectancy-Value Theory, Basic Psychological Needs Theory, and Social Identity Theory, this study aims to examine the impact of gender stereotypes on female exercise behavior and to test the chain mediation effects of psychological needs satisfaction in exercise and negative exercise emotions.

**Methods:** The study uses adapted scales for gender stereotypes, psychological needs satisfaction in exercise, exercise-related emotions, and exercise behavior to survey 790 women in China.

**Results:** The results show that gender stereotypes are significantly negatively associated with female exercise behavior. Both psychological needs satisfaction in exercise and negative exercise emotions mediate the relationship between gender stereotypes and female exercise behavior. Furthermore, psychological needs satisfaction and negative exercise emotions also jointly play a chain mediating role.

**Discussion:** Addressing gender stereotypes and fostering environments that support psychological needs fulfillment could improve women's engagement in exercise. Future interventions should focus on reducing gender bias in sports and promoting inclusive, supportive exercise environments to enhance women's participation in physical activity.

KEYWORDS

**physical activity participation, psychological theory, self-determination theory, sexism in sports, gender stereotypes**

## 1 Introduction

Physical exercise, as a regular, structured, and repetitive form of physical activity, is a key approach to improving health and preventing chronic diseases. It not only enhances physical fitness and promotes mental well-being, but also strengthens individuals' capacity for social adaptation, thus holding significant public health value (Eather et al., 2023; Sivaramakrishnan et al., 2024). However, existing studies indicate that participation in physical exercise among adults remains suboptimal globally, with women consistently showing lower levels of engagement than men (Walton et al., 2024). In 2022, approximately 31.3% of adults worldwide did not meet the recommended level of physical activity, with 33.8% of women falling short, compared to 28.7% of men (Strain et al., 2024). This gender disparity cannot be fully explained by biological differences or access to resources, and is more likely influenced by socio-cultural and structural factors. Therefore, investigating the underlying mechanisms that affect women's participation in physical exercise is not only essential for enhancing their health outcomes, but also crucial for advancing gender equity and achieving universal health goals.

In previous research on the attribution mechanisms and optimization strategies for female exercise behavior, factors such as physical exertion, family exercise environment, socioeconomic status, physical self-concept, and gender differences have been identified as antecedent variables influencing women's participation in physical exercise (Crossman et al., 2024; Moreno-Llamas et al., 2022; Peng et al., 2023; Schmidt et al., 2015). In recent years, as research has deepened and perspectives broadened, gender stereotypes—culturally embedded and rigid perceptions of male and female behavioral traits—have emerged as a potentially significant yet often overlooked factor influencing female participation in physical exercise (Gentile et al., 2018). Specifically, traditional gender roles tend to frame women within paradigms of softness and modesty while associating strength, competitiveness, and athleticism with masculinity (Hentschel et al., 2019; Plaza et al., 2017). These stereotypes are perpetuated through media narratives, educational settings, and everyday social interactions and are gradually internalized as the belief that physical exercise is inherently a male domain (Rasmussen et al., 2021). Within such a cultural context, women may not only face the risk of being labeled as "masculine" for engaging in sports. However, they may also experience diminished autonomy and a perceived lack of competence in exercise. These psychosocial barriers can ultimately reduce their motivation to participate and lead to behavioral withdrawal. Therefore, uncovering the mechanisms through which gender stereotypes affect female exercise behavior is crucial—not only for addressing health inequities, but also for providing empirical foundations to foster a more gender-inclusive exercise culture.

Once gender stereotypes are formed, they exert a broad influence on both individuals' psychology and behavior (Anglin et al., 2022). In the context of female physical exercise behavior, such stereotypical perceptions not only directly constrain willingness to participate but may also trigger a chain reaction that undermines the satisfaction of basic psychological needs in exercise and elicits negative exercise-related emotions, thereby forming a systematic mechanism of behavioral inhibition (Sunderji et al., 2024). According to Basic Psychological Needs Theory, three innate psychological needs—autonomy, competence, and relatedness—are fundamental drivers of human motivation and behavior (Deci and Ryan, 2000). When physical exercise is socially constructed as a 'masculine domain' due to prevailing gender stereotypes, women may be pressured to relinquish autonomous exercise choices because of perceived incongruence with traditional female roles, may question their competence due to stereotypes of inferior physical ability, or may feel socially excluded in male-dominated exercise environments. The prolonged frustration of these psychological needs not only diminishes intrinsic motivation for exercise but also contributes to the emergence of negative emotional responses such as shame and anxiety, which may further deepen resistance toward participation (Lloyd and Little, 2010). Thus, the fulfillment of basic psychological needs in exercise and negative exercise emotions may serve as important mediating mechanisms linking gender stereotypes to female exercise behavior.

In summary, this study is grounded in the Basic Psychological Needs Theory and aims to address the following core questions: How do gender stereotypes influence female exercise behavior? Do psychological needs satisfaction in exercise and negative exercise emotions serve as mediators in this relationship? Specifically, this study will examine the individual mediating effects of these two variables, as well as their combined mediating effect, to uncover the underlying psychological mechanisms through which gender stereotypes influence female exercise behavior.

## 2 Theoretical foundation and research hypotheses

### 2.1 Gender stereotypes and female exercise behavior

Gender stereotypes refer to the fixed patterns of cognition about the behaviors and personality traits attributed to men and women, which involve the generalization and summarization of the characteristics of the two sexes (Korlat et al., 2022). These stereotypes not only persist and influence social activities but also represent the general expectations people have of male and female members of society (Ellemers, 2018). Such gender role stereotypes serve as a precursor to social gender inequality, which leads to biased gender role expectations (Prentice and Carranza, 2002). Under the influence of these stereotypes, when individuals experience conflicts between their ideal self and actual self (such as diminished self-esteem, restricted personality, or violation), gender role conflicts arise (Good and Sanchez, 2010).

Regarding gender stereotypes, women are stereotypically viewed as possessing communion, meaning they seek relationship maintenance, desire belonging, and emphasize warmth and morality (Loeffler and Greitemeyer, 2023). In contrast, men are stereotypically viewed as possessing agency, meaning they are seen as pursuing goal achievement, taking task-oriented actions, and emphasizing confidence and competence (Hentschel et al., 2019). As a physical practice that reflects the oppositional relationship between the sexes, sports also construct corresponding stereotypes about the body, society, and sports (Plaza et al., 2017; Saemi et al., 2025). These gender differences are often stereotypically understood in exercise behavior, with men being perceived as having better endurance in exercise, while women are thought to possess more stable exercise habits (Themen and van Hooff, 2017). Specifically, in modern society, competitive sports are often associated with masculine traits such as large body size, strong muscles, and agility (Eccles and Harold, 1991). In contrast, women, who are generally smaller in stature, more flexible, and often affected by physiological events such as menstruation, pregnancy, childbirth, and menopause, are perceived as naturally less suited for intense physical sports (Liu et al., 2023; Sunderji et al., 2024). Women's sports also receive less attention in mass media coverage, which usually focuses more on the appearance or femininity of female athletes than on their athletic performance (Walton et al., 2024). These stereotypes influence women's participation in sports, as men are more likely to view themselves as stronger and more capable than women, thereby placing greater importance on sports participation (Gentile et al., 2018).

Expectancy-value theory suggests that individuals' beliefs about their competence, expectations of success, and task value influence their task choice and performance, and that these factors may be influenced by socialization into gender roles (Wigfield and Eccles, 2000). Existing research has shown that women may perceive their athletic abilities as inadequate due to physical or physiological reasons, which can make it difficult for them to engage in physical activities (Peng et al., 2023). Alternatively, they may view exercise as inconsistent with their feminine image of being delicate and quiet, often displaying negative behaviors such as fatigue, social withdrawal, or apathy during exercise (Slater and Tiggemann, 2010). Lindwall and Hassmén (2004) noted that women tend to reduce their willingness to participate in physical activity when they perceive certain sports to be incompatible with their gender identity. This also suggests that gender stereotypes in sports activities have a profound impact on participants' gender identity and sports behaviors, particularly in the perception of masculine sports, which may have a constraining effect on women's participation in and behaviors within sports (Sobal and Milgrim, 2019). Therefore, female exercise behavior may be influenced by gender stereotypes in the exercise context, and when women's exercise behavior contradicts socially accepted gender stereotypes, it may lead to negative consequences for their exercise behavior. Based on this, we propose the following research hypothesis:

> *H1*: Gender stereotypes negatively predict female exercise behavior.

## 2.2 The mediating role of psychological needs satisfaction in exercise

Basic Psychological Needs Theory (BPNT) is a branch of Self-Determination Theory and is one of the most widely used frameworks in the study of exercise behavior (Westerskov Dalgas et al., 2024). BPNT posits that humans are born with three basic psychological needs: autonomy, competence, and relatedness (Deci and Ryan, 2000). Autonomy refers to an individual's desire for their behavior to be freely chosen and decided upon without external control. Competence refers to the desire to experience a sense of mastery when interacting with the social environment. Relatedness refers to the need to feel understood and supported by others, thereby experiencing a sense of belonging (Ryan, 2017). In the context of exercise, psychological needs satisfaction refers to the extent to which the external environment fulfills an individual's exercise-related psychological needs. It is the essential "nutrient" that supports the internalization of psychological engagement in exercise and the pursuit of active exercise behavior (Mack and Wilson, 2021).

Traditional gender views often categorize women as submissive, gentle, and passive, and women who engage in exercise may conflict with the societal expectations associated with these traits (Chalabaev et al., 2013; Schaillee et al., 2021). When exercise behavior conflicts with gender stereotypes, it may lead women to feel that their exercise choices lack societal respect and recognition, thereby damaging their autonomy in exercise participation and practice (Lloyd and Little, 2010). Additionally, the influence of gender stereotypes may trigger avoidance motivations, limiting opportunities for skill development and mastery of exercise abilities, thereby impacting competence. At the same time, when exercise behavior deviates from gender stereotypes, women may face increased stigma (Peng et al., 2023), such as being labeled as "tomboys," which can reduce self-esteem and lead to social withdrawal in exercise settings, ultimately preventing the fulfillment of the need for relatedness.

Basic Psychological Needs Theory also suggests that the degree to which individuals internalize external requirements, values, and norms depends on their psychological needs within activities, and the extent of psychological needs satisfaction activates behaviors at varying levels of motivation (Deci and Ryan, 2000) In the promotion of exercise, satisfying psychological needs enhances intrinsic interest and enjoyment in exercise (Westerskov Dalgas et al., 2024), thereby further increasing an individual's exercise participation (Dunton et al., 2023). Conversely, when an individual's psychological exercise needs are unmet, they may suffer significant psychological costs, resulting in "negative adaptation," such as psychological alienation, deprivation, and inefficiency (Gunnell et al., 2013). For women, when their competence, autonomy, and relatedness needs in exercise are not fulfilled, it further strengthens their avoidance motivation toward exercise, negatively impacting their exercise behavior (Lloyd and Little, 2010). In conclusion, society's gender stereotypes regarding women in sports lead to a lower degree of recognition for women's participation in physical exercise compared to men. This lack of recognition weakens their satisfaction with psychological exercise needs, further diminishing their engagement in exercise. Based on this, we propose the following research hypothesis:

> *H2*: Psychological needs satisfaction in exercise mediates the relationship between gender stereotypes and female exercise behavior.

## 2.3 The mediating role of negative exercise emotions

Negative exercise emotions refer to subjective emotional experiences and cognitive evaluations that are directly related to physical exercise, occurring during or shortly after the exercise period, characterized by distinctly negative features (Lane and Lovejoy, 2001). Compared to males, females experience more anxiety, distress, and lower satisfaction due to traditional societal gender stereotypes (Hively and El-Alayli, 2014). When their exercise behavior contradicts their expectations, it limits their exercise engagement and negatively impacts their psychological adaptation and subsequent behavioral choices (Bevan et al., 2021).

The impact of gender stereotypes on women's negative exercise emotions primarily manifests in two ways: on one hand, women form complex psychological states, such as cognition, emotion, and self-esteem, based on external support and recognition of their exercise behavior (Laird et al., 2016; Levy and Ebbeck, 2005). If women perceive their exercise behavior as unsupported by society, which contradicts traditional gender stereotypes, they are more likely to experience negative emotions like burnout and anxiety during exercise (He et al., 2024; Hively and El-Alayli, 2014). On the other hand, if their exercise behavior receives more external support, recognition, and attention, the gender role conflict they feel during exercise will be less pronounced, leading to more positive exercise emotions such as confidence and satisfaction (Asztalos et al., 2012).

According to Social Identity Theory, the formation of group stereotypes also follows a psychological process of social comparison (Hornsey, 2008). Gender stereotypes can trigger social comparison in women, diminishing their exercise self-efficacy and positioning them at a disadvantage compared to men, thus reinforcing their negative emotional experiences in exercise contexts (Van Loo et al., 2013). Existing research has shown that the degree of positive or negative emotional change experienced during and after exercise significantly influences subsequent exercise behavior decisions (Bernstein et al., 2019). If participants experience positive emotions during exercise, this can motivate further participation and promote exercise adherence. Conversely, if participants fail to derive satisfaction or positive feelings from exercise, their exercise intentions are likely to decrease, negatively impacting their exercise persistence (Catellier and Yang, 2013; Williams et al., 2008).

In conclusion, when women's exercise behavior significantly deviates from the long-established gender role expectations shaped by traditional societal gender stereotypes, this deviation may trigger a series of negative exercise emotions. This psychological reaction not only hinders women's positive attitudes toward exercise but may also further weaken their motivation and actual participation in physical exercise. Based on this, the study proposes the following research hypothesis:

> *H3*: Negative exercise emotions mediate the relationship between gender stereotypes and female exercise behavior.

## 2.4 The chain mediating role of psychological needs satisfaction in exercise and negative exercise emotions

Research on individual subjective well-being indicates that individuals can promote positive emotions when their basic psychological needs are met during physical activity, thus enhancing their subjective well-being (Gunnell et al., 2013). Conversely, if these needs are poorly satisfied, negative emotions increase, leading to a decline in well-being (Chang et al., 2015). Sheldon (2012) similarly found that autonomy, competence, and relatedness need to predict positive emotions across different cultures and argued that these needs are rooted in human genetics. When the environment provides sufficient support, the satisfaction of basic psychological needs leads to the emergence of positive emotions (Sheldon, 2012). Specifically, when individuals' needs are fulfilled, they tend to develop in positive directions, such as self-improvement and self-enhancement (Lin and Chan, 2020). However, such fulfillment is not automatic and requires support and assistance from the external environment (Deci and Ryan, 2008). Existing studies also suggest that when women receive more support from significant others, their motivation, enjoyment, and happiness in exercise increase significantly (Cho et al., 2023).

However, most sports carry traits of masculinity, such as aggressiveness, competitiveness, and adventurousness, which contradict the socially advocated feminine traits. Under the influence of such gender stereotypes, women find it difficult to escape society's expectations of their gender roles (Ellemers, 2018), and experience conflict between exercise and their gender role (Vieira Sosa et al., 2025). This leads to feelings of being unsupported and unrecognized in their exercise behavior (Patnode et al., 2010). When women's exercise behavior fails to perceive support from others, their psychological exercise needs remain unmet, further triggering negative psychological reactions (Gunnell et al., 2013).

In conclusion, the presence of gender stereotypes may significantly undermine women's satisfaction with psychological exercise needs, which, through psychological mechanisms, induces negative exercise emotions. These negative emotions not only affect women's psychological state but also suppress the persistence and frequency of their exercise behavior. Based on this, the study proposes the following research hypothesis:

> *H4*: Psychological needs satisfaction in exercise and negative exercise emotions mediate the relationship between gender stereotypes and female exercise behavior in a chain mediation.

In summary, this study constructs a conceptual model of the impact of gender stereotypes, psychological needs satisfaction in exercise, and negative exercise emotions on female exercise behavior. The relationships between the specific variables are shown in Figure 1.

# 3 Research design

## 3.1 Research sample

This study was conducted from March to April 2024, utilizing a combination of offline and online questionnaire surveys targeting the female population. To ensure data quality, screening mechanisms such as attention-check questions and response time controls were incorporated during the questionnaire design phase to eliminate invalid responses. For the offline survey, the research team selected community service centers, educational institutions, and public sports venues in cities across eastern, central, and western provinces of China

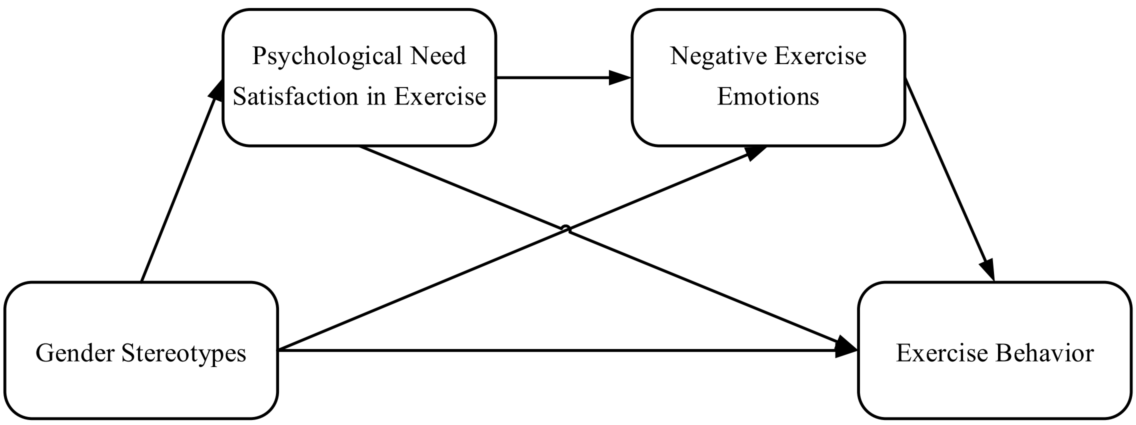


FIGURE 1
Conceptual model diagram.

and distributed 400 questionnaires using convenience sampling. A total of 373 questionnaires were returned, among which 339 were valid after excluding incomplete or invalid responses, resulting in a valid response rate of 90.88%. For the online survey, questionnaires were distributed via the Wenjuanxing platform and disseminated through social media using snowball sampling techniques. A total of 513 responses were collected, with 451 deemed valid after screening, yielding a valid response rate of 87.91%. A total of 790 valid questionnaires were obtained. The sample encompasses a wide geographic area and exhibits considerable diversity in terms of age, educational background, and income level, thereby possessing a certain degree of representativeness. Basic information on the sample is shown in Table 1.

## 3.2 Measurement tools

### 3.2.1 Gender stereotypes

Gender stereotypes are culturally embedded cognitive biases, such as the beliefs that women are more emotional and men are more suited to leadership. This study focuses on gender stereotypes in the sports domain, given its prominent role in gender role socialization and its suitability for examining the effects of stereotypes within a specific situational context. The scale was adapted from relevant work by Sage and Loudermilk (1979), Huang and Zhang (2025), and Schmader et al. (2004), and refined to suit the current study (Huang and Zhang, 2025; Sage and Loudermilk, 1979; Schmader et al., 2004). Seven items were selected, such as "Social expectations of women's participation in sports are much lower than men's," which were rated on a 7-point Likert scale (1 for "strongly disagree," 7 for "strongly agree"), with higher scores indicating higher levels of stereotyping. In this study, the Cronbach's α coefficient for this scale was 0.946.

### 3.2.2 Exercise behavior

In this study, "physical exercise" is defined as planned, structured physical activity undertaken during leisure time with a certain level of intensity, aimed at improving or maintaining physical health and fitness. Participants were asked to report activities including, but not limited to, jogging, running, aerobics, yoga, swimming, cycling, strength training, badminton, tennis, and basketball. Routine physical activities such as commuting or household chores were excluded from the analysis. This study employed the revised Physical Activity Rating Scale-3 (PARS-3), developed by Liang (1994), which has been widely used to assess physical exercise behavior in the Chinese context (Liang, 1994). This scale uses a 5-point Likert scale, with scores ranging from 1 to 5. According to the evaluation criteria, the exercise load score is calculated as: intensity × (duration - 1) × frequency, with a maximum score of 100 and a minimum score of 0, representing exercise behavior. In this study, the Cronbach's α coefficient for this scale was 0.880.

### 3.2.3 Psychological needs satisfaction in exercise

The measurement of psychological needs satisfaction in exercise is represented by the Psychological Needs Satisfaction in Exercise Scale (PNSE) developed by Wilson et al. (2006). This scale includes three dimensions: competence needs, autonomy needs, and relatedness needs. The scale is divided into these three dimensions, each containing 6 items, for a total of 18 items. The competence dimension includes items such as "I feel confident in my ability to complete challenging exercise tasks"; the autonomy dimension includes items such as "I can freely choose the exercise activities I want to engage in"; and the relatedness dimension includes items such as "In exercise, I feel a good connection and interaction with those I exercise with." The items are rated on a 7-point Likert scale, where 1 represents "strongly disagree" and 7 represents "strongly agree," with higher scores indicating greater satisfaction of psychological needs in exercise. In this study, the Cronbach's α values for each dimension are 0.929, 0.947, and 0.947, respectively, with a total Cronbach's α of 0.950, indicating a high level of internal consistency and reliability of the scale.

### 3.2.4 Negative exercise emotions

The measurement of negative exercise emotions was adapted from the negative exercise emotion subscale of the Physical Activity Affect

TABLE 1 Basic information of the sample.

| Statistical variable | Category | Frequency | Percentage (%) |
|---|---|---|---|
| Gender | Male | 0 | 0 |
| | Female | 790 | 100.0 |
| Age | Under 25 years | 147 | 18.6 |
| | 25–35 years | 248 | 31.4 |
| | 36–45 years | 226 | 28.6 |
| | Over 45 years | 169 | 21.4 |
| Education level | High school or below | 242 | 30.6 |
| | Associate degree | 281 | 35.6 |
| | Bachelor's degree | 197 | 24.9 |
| | Master's degree or above | 70 | 8.9 |
| Monthly income | 3,000 or below | 235 | 29.7 |
| | 3,001–5,000 | 288 | 36.5 |
| | 5,001–8,000 | 154 | 19.5 |
| | Above 8,000 | 113 | 14.3 |

Scale developed by Lox et al. (2000) (Lox et al., 2000), this study made appropriate modifications to the original scale to better fit the context of this research. The specific modifications involved adjusting the language of certain items to more closely align with the emotional experiences of female participants during exercise. The final modified scale consists of four items, such as: "I feel that exercise is a burden to me, rather than an enjoyment." The items are rated on a 7-point Likert scale, where 1 represents "strongly disagree" and 7 represents "strongly agree," with higher scores indicating higher levels of negative exercise emotions in women. In this study, the Cronbach's α for this scale was 0.916.

### 3.3 Data analysis methods

This study is a cross-sectional questionnaire survey designed to explore the influencing factors of female exercise behavior. Data analysis was conducted using SPSS 22.0 and AMOS 24.0. SPSS 22.0 was used for data entry, descriptive statistics, and correlation analysis, as well as for conducting hierarchical regression analyses to examine the direct effects among variables and the preliminary role of mediators. Additionally, AMOS 24.0 was employed to perform Confirmatory Factor Analysis (CFA) and Structural Equation Modeling (SEM). The significance of the chained mediation effect was tested using the Bootstrap method with 5,000 resamples. While hierarchical regression analysis focuses on decomposing local relationships among variables, structural equation modeling (SEM) combined with the Bootstrap method validates complex pathways in terms of overall model fit and statistical robustness. These two analytical approaches complement each other, thereby ensuring the reliability of the analysis results.

## 4 Results and analysis

### 4.1 Control and testing of common method bias

This study employed anonymous responses and mitigated common method bias through the use of reverse-coded items and mixed item ordering. However, since data were collected via self-reports, some degree of common method bias was unavoidable. For this reason, all question items were tested using the Harman's single-factor test. The results indicated that there were 6 factors with eigenvalues greater than 1, and the first unrotated factor accounted for 37.613% of the variance, which is below the 40% threshold. This suggests that the common method bias is acceptable and does not significantly affect the validity of subsequent analyses.

### 4.2 Confirmatory factor analysis

This study conducted confirmatory factor analysis (CFA) using AMOS 24.0 software. The results indicated that the measurement model demonstrated a good fit: $\chi^2/df = 1.443$, RMR = 0.080, GFI = 0.952, AGFI = 0.941, NFI = 0.974, TLI = 0.991, CFI = 0.992, RMSEA = 0.024. As shown in Table 2, all factor loadings for the items were greater than 0.6, and the composite reliabilities (CR) for all variables exceeded the recommended threshold of 0.7. Additionally, the average variance extracted (AVE) was also higher than the recommended level of 0.50, indicating that the scale demonstrates good convergent validity. As presented in Table 3, the square roots of all AVEs were greater than the correlations between the corresponding variables, confirming that the scale possesses good discriminant validity.

### 4.3 Descriptive statistics and correlation analysis

To explore the relationships among gender stereotypes, psychological needs satisfaction in exercise, negative exercise emotions, and exercise behavior, statistical and correlation analyses were conducted on these research variables. The results are shown in Table 4. Gender stereotypes were significantly negatively correlated with psychological needs satisfaction in exercise ($\beta = -0.229$, $p < 0.01$) and exercise behavior ($\beta = -0.437$, $p < 0.01$), and significantly positively correlated with negative exercise emotions ($\beta = 0.497$, $p < 0.01$). Psychological needs satisfaction in exercise was significantly negatively correlated with negative exercise emotions ($\beta = -0.298$, $p < 0.01$) and significantly positively correlated with exercise behavior ($\beta = 0.516$, $p < 0.01$). Negative exercise emotions were significantly negatively correlated with exercise behavior ($\beta = -0.462$, $p < 0.01$). The significant correlations among the variables align with the direction of the research hypotheses, providing a necessary foundation for subsequent model analysis.

### 4.4 Regression model testing

Hierarchical regression analysis was used to establish the regression models, with the results presented in Table 5. Model 3 shows that the regression coefficient for gender stereotypes on female exercise behavior is −0.437 ($p < 0.001$), indicating that the level of gender stereotypes negatively predicts female exercise behavior, supporting Hypothesis H1. Models 1 and 2 show that the regression coefficients for gender stereotypes on female psychological needs satisfaction in exercise and negative exercise emotions are −0.189 ($p < 0.001$) and 0.499 ($p < 0.001$), respectively, indicating that the level of gender stereotypes negatively predicts psychological needs satisfaction in exercise and positively predicts negative exercise emotions in women. Models 4 and 5 show that the regression coefficients for psychological needs satisfaction in exercise and negative exercise emotions on female exercise behavior are 0.521 ($p < 0.001$) and −0.462 ($p < 0.001$), respectively, suggesting that psychological needs satisfaction positively predicts female exercise behavior, while negative exercise emotions negatively predict it. Additionally, Models 6, 7, and 8 show that when the variables of psychological needs satisfaction and negative exercise emotions are introduced separately or together, although gender stereotypes still predict female exercise behavior, the strength of the relationship weakens. This suggests that psychological needs satisfaction and negative exercise emotions may mediate the relationship between gender stereotypes and female exercise behavior, providing essential support for the subsequent mediation effect testing.

TABLE 2 Questionnaire items.

| Variable | Item | Load | SD | AVE | CR |
|---|---|---|---|---|---|
| Gender stereotypes | GS1 | 0.857 | 0.186 | 0.740 | 0.952 |
| | GS2 | 0.856 | | | |
| | GS3 | 0.858 | | | |
| | GS4 | 0.887 | | | |
| | GS5 | 0.889 | | | |
| | GS6 | 0.846 | | | |
| | GS7 | 0.828 | | | |
| Competence | COM1 | 0.839 | 0.180 | 0.684 | 0.928 |
| | COM2 | 0.856 | | | |
| | COM3 | 0.871 | | | |
| | COM4 | 0.813 | | | |
| | COM5 | 0.775 | | | |
| | COM6 | 0.804 | | | |
| Autonomy | AUT1 | 0.878 | 0.181 | 0.751 | 0.948 |
| | AUT2 | 0.866 | | | |
| | AUT3 | 0.871 | | | |
| | AUT4 | 0.876 | | | |
| | AUT5 | 0.859 | | | |
| | AUT6 | 0.850 | | | |
| Relatedness | REL1 | 0.847 | 0.161 | 0.746 | 0.946 |
| | REL2 | 0.853 | | | |
| | REL3 | 0.884 | | | |
| | REL4 | 0.874 | | | |
| | REL5 | 0.854 | | | |
| | REL6 | 0.868 | | | |
| Negative exercise emotions | NEE1 | 0.853 | 0.164 | 0.775 | 0.932 |
| | NEE2 | 0.887 | | | |
| | NEE3 | 0.930 | | | |
| | NEE4 | 0.849 | | | |
| Exercise behavior | EB1 | 0.865 | 0.103 | 0.713 | 0.882 |
| | EB2 | 0.878 | | | |
| | EB3 | 0.788 | | | |

TABLE 3 Correlation coefficients of latent variables.

| Variables | GS | COM | AUT | REL | NEE | EB |
|---|---|---|---|---|---|---|
| GS | 0.860 | | | | | |
| COM | −0.173 | 0.827 | | | | |
| AUT | −0.155 | 0.539 | 0.867 | | | |
| REL | −0.140 | 0.509 | 0.678 | 0.864 | | |
| NEE | 0.505 | −0.194 | −0.178 | −0.178 | 0.880 | |
| EB | −0.340 | 0.519 | 0.467 | 0.419 | −0.295 | 0.844 |

The diagonal data of the matrix represent the square root of the AVE values, and the lower half of the matrix represents the correlation coefficient.

TABLE 4 Results of descriptive statistics and correlation analysis.

| Variables | *M* | SD | GS | PESE | NEE | EB |
|---|---|---|---|---|---|---|
| GS | 4.454 | 1.700 | 1 | | | |
| PESE | 4.668 | 1.374 | −0.229** | 1 | | |
| NEE | 4.214 | 1.713 | 0.497** | −0.298** | 1 | |
| EB | 33.172 | 29.721 | −0.437** | 0.516** | −0.462** | 1 |

**$p < 0.01$; PESE, Psychological Needs Satisfaction in Exercise.

TABLE 5 Results of regression analysis.

| Variables | PESE | NEE | EB | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Model 1 | Model 2 | Model 3 | Model 4 | Model 5 | Model 6 | Model 7 | Model 8 |
| Age | 0.032 | −0.026 | 0.002 | −0.015 | −0.013 | −0.009 | −0.007 | −0.013 |
| Education level | −0.067 | −0.052 | 0.011 | 0.032 | −0.014 | 0.031 | −0.006 | 0.017 |
| Monthly income | −0.072 | 0.029 | 0.006 | 0.058 | 0.036 | 0.029 | 0.016 | 0.034 |
| GS | −0.189*** | 0.499*** | −0.437*** | | | −0.333*** | −0.274*** | −0.230*** |
| PESE | | | | 0.521*** | | 0.443*** | | 0.399*** |
| NEE | | | | | −0.462*** | | −0.326*** | −0.228*** |
| $R^2$ | 0.059 | 0.250 | 0.438 | 0.522 | 0.215 | 0.643 | 0.271 | 0.413 |
| Adj. $R^2$ | 0.054 | 0.246 | 0.191 | 0.272 | 0.211 | 0.413 | 0.266 | 0.409 |
| *F* | 12.344*** | 65.487*** | 46.465*** | 73.364*** | 53.657*** | 91.898*** | 58.268*** | 91.898*** |

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

### 4.5 Mediation effect testing

A structural equation model was used to establish the relationship model with gender stereotypes as the independent variable, exercise behavior as the dependent variable, and psychological needs satisfaction in exercise and negative exercise emotions as mediating variables (see Figure 2). The model fit statistics are as follows: $\chi^2$/df = 1.611, RMR = 0.127, GFI = 0.947, AGFI = 0.935, NFI = 0.969, TLI = 0.986, CFI = 0.988, RMSEA = 0.028. These statistics indicate that the measurement model has good fit. As shown in Figure 2, gender stereotypes significantly negatively affect exercise behavior (β = −0.220, $p < 0.001$), further confirming Hypothesis H1. Additionally, gender stereotypes significantly negatively affect psychological needs satisfaction in exercise (β = −0.252, $p < 0.001$) and significantly positively affect negative exercise emotions (β = 0.482, $p < 0.001$). Psychological needs satisfaction in exercise significantly negatively affects negative exercise emotions (β = −0.208, $p < 0.001$) and significantly positively affects exercise behavior (β = 0.482, $p < 0.001$). Negative exercise emotions significantly negatively affect exercise behavior (β = −0.218, $p < 0.001$).

To verify the mediating effects of psychological needs satisfaction in exercise and negative exercise emotions in the path through which gender stereotypes affect female exercise behavior, this study used the Bootstrap method for significance testing of the mediation effects, employing AMOS 24.0 software. A total of 5,000 bootstrap resamples were conducted on 790 samples, and if the 95% confidence interval does not contain 0, it indicates the presence of a mediation effect. The Bootstrap analysis for the significance testing of the mediation effects in this study is shown in Table 4.

As shown in Table 6, psychological needs satisfaction in exercise and negative exercise emotions exert significant mediating effects in the relationship between gender stereotypes and exercise behavior. The total indirect effect was β = −0.188 (95% CI [−0.240, −0.141], $p < 0.001$), accounting for 52.08% of the total effect. Specifically, gender stereotypes indirectly influenced exercise behavior through psychological needs satisfaction in exercise, with a standardized indirect effect of β = −0.096 (95% CI [−0.133, −0.066], $p < 0.001$), accounting for 26.59% of the total effect. This indicates that the mediation pathway is significant, supporting Hypothesis H2. In addition, gender stereotypes also indirectly influenced exercise behavior through negative exercise emotions, with a standardized indirect effect of β = −0.083 (95% CI [−0.119, −0.050], $p < 0.001$), accounting for 22.99% of the total effect, thereby supporting Hypothesis H3. Furthermore, gender stereotypes influenced exercise behavior indirectly through a sequential chain of psychological needs satisfaction in exercise followed by negative exercise emotions, with an effect size of β = −0.009 (95% CI [−0.015, −0.005], $p < 0.001$), accounting for 2.49% of the total effect. This chain mediation path was also significant, providing support for Hypothesis H4.

## 5 Discussion

### 5.1 The impact of gender stereotypes on female exercise behavior

The results of this study indicate that gender stereotypes significantly negatively predict female exercise behavior, showing that women who hold higher levels of gender stereotypes in sports tend to have a noticeable decline in their exercise participation. This result is somewhat consistent with previous research, which has generally focused on the overall impact of gender stereotypes on sports

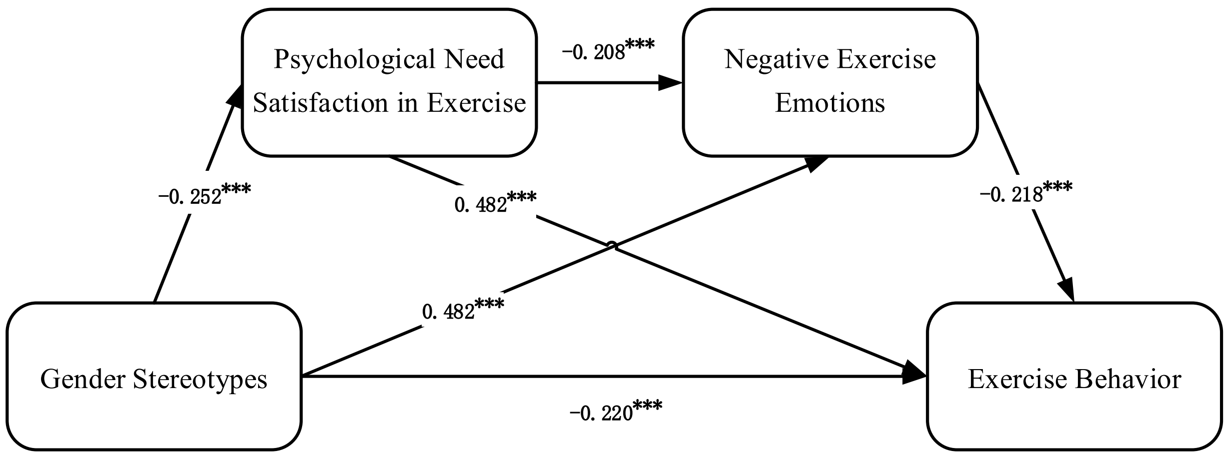


FIGURE 2
Conceptual model main path coefficient diagram. *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

TABLE 6 Mediating effects test.

| Path | Effect value | SE | *p* | Bias-corrected 95% CI | | Percentage (%) |
|---|---|---|---|---|---|---|
| | | | | Lower | Upper | |
| Total effect | −0.361 | 0.027 | *** | −0.413 | −0.308 | 100 |
| Direct effect | −0.173 | 0.033 | *** | −0.240 | −0.109 | 47.92 |
| Indirect effects | −0.188 | 0.025 | *** | −0.240 | −0.141 | 52.08 |
| GS → PESE→EB | −0.096 | 0.017 | *** | −0.133 | −0.066 | 26.59 |
| GS → NEE → EB | −0.083 | 0.018 | *** | −0.119 | −0.050 | 22.99 |
| GS → PESE→NEE → EB | −0.009 | 0.002 | *** | −0.015 | −0.005 | 2.49 |

***$p < 0.001$.

performance and participation, emphasizing how psychological and cultural factors influence gender differences in sports (Chalabaev et al., 2013). However, this study further explores the specific mechanisms by which gender stereotypes influence women's exercise behavior. Building on previous research, this study suggests that the negative impact of gender stereotypes on female exercise behavior can be explored from both social-cultural and individual psychological perspectives.

First, from a social-cultural perspective, traditional social structures generally favor the allocation of sports resources and power to men, shaping biases and discrimination against women's participation in sports (Evans and Pfister, 2021). Influenced and reinforced by traditional gender culture and societal gender role expectations, some women unconsciously internalize these as gender role stereotypes, thereby developing a value-based understanding of societal gender roles (Korlat et al., 2022). If women align with these gender values, they may develop a psychological rejection of sports, which leads to a natural disregard, devaluation, or even denial of physical exercise and its value (He et al., 2024). From an individual psychological perspective, emotion and memory theory highlights that an individual's memory system stores emotional experiences associated with task completion (Tyng et al., 2017). When women face social evaluations, their cognitive memories of past exercise behaviors may shape their beliefs, causing them to view delicate, gentle, and calm behavior as more socially acceptable than the active, agile, and strong attributes associated with sports. Furthermore, to maintain self-esteem and avoid being stigmatized as "tomboys" or "unfeminine," women may display lower levels of activity and persistence in exercise.

In summary, under the influence of gender stereotypes in society, women are more likely to adopt a "socially acceptable" mindset in exercise to gain approval from others. This psychological tendency undoubtedly has a significant negative impact on women's exercise behavior.

## 5.2 The mediating role of psychological needs satisfaction in exercise

The results of this study indicate that psychological needs satisfaction in exercise mediates the negative impact of gender stereotypes on female exercise behavior: stereotypes reduce this satisfaction, which in turn suppresses exercise participation. Previous studies have shown that when basic psychological needs are satisfied, individuals tend to engage more actively with their environment and participate in behaviors associated with positive outcomes. Conversely, when basic psychological needs are thwarted or unmet, individuals endure significant psychological costs and are more prone to "negative adaptation" behaviors (Vansteenkiste et al., 2020). For example, Orkibi and Ronen (2017) found that the satisfaction of basic psychological needs significantly positively predicted prosocial behaviors and well-being (Orkibi and Ronen, 2017). Yan et al. (2024) demonstrated that when adolescents possess positive exercise cognition and their basic psychological needs (such as autonomy, competence, and relatedness) are satisfied, they are more likely to engage in regular exercise behavior (Yan et al., 2024).

In line with these findings, this study also reveals that the satisfaction of psychological needs in exercise significantly promotes women's exercise behavior. However, this study goes a step further by not only focusing on the effect of needs satisfaction itself but also tracing its origins. It clearly identifies gender stereotypes—as an external sociocultural structure—as a key factor undermining women's ability to satisfy their psychological needs. This finding also supports self-determination theory, which posits that basic psychological needs mediate the development between external environments and individuals' internal growth (Deci and Ryan, 2000). Any event that prevents the fulfillment of these needs generates negative effects, leading to a decline in internal motivation and a decrease in behavioral initiative (Dysvik et al., 2013). For instance, social stigma, as an external pressure mechanism, triggers secondary evaluations by individuals, negatively impacting their exercise motivation through the satisfaction of psychological needs (Liu et al., 2021). On the contrary, Shannon et al. (2020) noted that mindfulness, as an internal support mechanism, can enhance individuals' self-regulation abilities and satisfaction of basic psychological needs, thereby reducing stress and improving well-being (Shannon et al., 2020). In this study, however, gender stereotypes hinder the satisfaction of women's psychological needs in exercise, leading to negative effects on subsequent exercise behavior.

Specifically, gender stereotypes lead women to subconsciously perceive sports as more aligned with men, while the self is expected to remain quiet and composed (Hermann and Vollmeyer, 2016; Spence and Sawin, 2014). This belief causes women to overlook their personal growth and development in exercise, reducing the likelihood of actively engaging in physical activity and failing to satisfy their autonomy needs. Additionally, they are less willing to challenge moderate or high-difficulty sports, thus failing to meet their competence needs. They also struggle to form good relationships with others during exercise, preventing the satisfaction of their relatedness needs. When women's psychological exercise needs are unmet, they develop avoidance coping strategies, leading to a decrease in exercise behavior.

## 5.3 The mediating role of negative exercise emotions

The results of this study indicate that negative exercise emotions significantly mediate the relationship between gender stereotypes and female exercise behavior, suggesting that gender stereotypes can indirectly suppress women's exercise behavior by triggering negative exercise emotions. This is consistent with the emotional pathways of studies that have explored the negative impact of general negative life events on physical activity behavior by inducing negative workout emotions in individuals (Bourke et al., 2021; Lucibello et al., 2023). However, the present study focuses on the unique influence of a specific socio-cultural antecedent variable, "gender stereotypes," on negative exercise emotions and behaviors in the female population, and reveals pathways that differ from those of general stressors. This study proposes that the mediating effect of negative exercise emotions between gender stereotypes and female exercise behavior operates through three main mechanisms:

First, from a socio-psychological perspective on exercise, a positive leisure exercise environment promotes feelings of relaxation and comfort, effectively reducing negative exercise emotions and enhancing exercise behavior (Li, 2024). However, under the influence of gender stereotypes, current society generally fosters the view that sports represent a male-oriented display of athleticism (Plaza et al., 2017), with women typically expected to play a supportive role in men's sports. This exercise environment somewhat suppresses women's enthusiasm for participating in physical exercise, affecting their perceptions and attitudes toward it.

Second, from the perspective of self-worth and cognition, when women experience intense gender role conflicts during exercise, they receive significant information related to adversity and frustration (Myre et al., 2023). The pervasive gender stereotypes transmitted by society can alter women's cognitive structures around exercise, making their understanding of its value and significance increasingly narrow, unclear, and irrational. As a result, they become more likely to exhibit negative, disengaged, and aimless behaviors during exercise, with their participation becoming more disorganized, tedious, and unsustainable.

Third, according to the Expectancy-Value Theory, gender stereotypes in the cultural environment create a bias between the ideal self and the real self for women in the context of exercise (Eccles and Harold, 1991). When this discrepancy between reality and societal expectations occurs, it often leads to strong feelings of inadequacy and other negative emotions. Under the influence of psychological defense mechanisms, women may reduce their participation in exercise as a way of coping with the self-deprecating emotional reactions caused by internalizing external negative evaluations during exercise.

## 5.4 The chain mediating role of psychological needs satisfaction in exercise and negative exercise emotions

The results of the mediation effect testing in this study indicate that psychological needs satisfaction in exercise and negative exercise emotions have a mediating effect on the chain between gender stereotypes and female exercise behavior. Although the effect size of the chain mediation path is relatively small (standardized effect = −0.009, 2.49% of the total effect), its confidence interval does not include zero, indicating statistical significance. Theoretically, it reveals how gender stereotypes affect women's exercise behavior through a layered psychological process—from reduced motivation to increased emotional exhaustion—gradually weakening their willingness to participate in physical activity. The study found that psychological needs satisfaction significantly negatively predicts negative exercise emotions, which is consistent with previous research (Gunnell et al., 2013). For example, a specialized survey of athletes revealed that when athletes' basic psychological needs are effectively met during exercise, they tend to display more positive emotional experiences, and this state of satisfaction shows a significant negative correlation with exercise burnout and negative emotions (Bartholomew et al., 2011).

Moreover, previous research has thoroughly confirmed that when individuals perceive support from others, it not only significantly enhances their intrinsic motivation for engaging in physical exercise but also actively promotes the optimization and enhancement of their psychological functions (Stevens et al., 2020). Specifically, this social support helps meet individuals' basic psychological needs, such as autonomy, competence, and relatedness, during exercise, which significantly boosts their psychological satisfaction with exercise behavior and overall psychological well-being. In studies examining gender differences in sports, it has been noted that, compared to men, women face stronger social comparisons regarding physical appearance and athletic performance (Ferguson et al., 2015), and their motivation to maintain positive psychological health outcomes tends to be shorter-lived (Vlachopoulos, 2008), with more negative self-evaluations (Adam et al., 2021). When gender roles contradict traditional societal gender stereotypes, women feel that their exercise behavior is not recognized or supported by others, which reduces their psychological needs satisfaction in exercise.

However, psychological needs satisfaction is one of the internal motivational systems driving women to engage in physical exercise, and it affects the psychological processes related to the development of their exercise emotions (Lloyd and Little, 2010). Therefore, when psychological exercise needs are unmet, they intensify women's negative exercise emotional experiences, making it difficult for women to actively engage in exercise behavior. From this, it can be concluded that psychological needs satisfaction in exercise and negative exercise emotions are the continuous links that connect gender stereotypes to female exercise behavior.

# 6 Conclusions and future directions

## 6.1 Conclusions and implications

By constructing a structural equation model, this study systematically reveals, both theoretically and empirically, the negative impact of gender stereotypes on women's exercise behavior and its underlying psychological mechanisms. The findings indicate that gender stereotypes not only directly suppress women's exercise behavior, but also indirectly weaken it through a chain-mediated pathway involving psychological needs satisfaction in exercise and negative exercise emotions. Furthermore, the study confirms that satisfaction of psychological needs in exercise negatively predicts negative exercise emotions and positively predicts exercise behavior, while negative exercise emotions significantly inhibit women's participation in physical activity.

These findings contribute to theory in two main aspects. First, the study breaks through the limitations of previous research, which have focused on physiological differences, socioeconomic status, or family role distribution as the primary factors influencing women's exercise behavior. By introducing gender stereotypes as a socio-psychological dimension, the study enriches the theoretical framework of exercise behavior research. Second, by clarifying the mediating mechanisms of psychological needs satisfaction in exercise and the negative emotions associated with exercise, the study expands the application of basic psychological needs theory and emotional experience within exercise contexts, offering new explanatory pathways for understanding individual exercise decision-making under socio-cultural influences.

Based on the above conclusions, the study offers the following recommendations to promote women's participation in physical activity. First, society should actively dismantle gender stereotypes surrounding women's involvement in sports and build a gender-friendly exercise culture. Since sports themselves are not inherently gendered, the public should discard gender-labeling perceptions of sports and enhance women's sense of social recognition and belonging in exercise contexts. Second, it is crucial to advocate for and implement "androgynous education," encouraging women to transcend stereotypical gender roles and develop a flexible and multifaceted self-concept, thereby boosting their psychological autonomy and motivation in exercise participation. Third, sports organizations and businesses should pay attention to the personalized needs of women by developing exercise programs and services that align with their physical characteristics and personal interests, thereby enhancing their sense of competence, belonging, and willingness to participate in the long term. Finally, to alleviate potential negative emotions that may arise during exercise, it is essential to strengthen psychological support resources in sports, providing women with professional services in emotional regulation and counseling, which will further promote stable and healthy exercise behavior.

# 7 Limitations and future directions

The limitations of this study are as follows, and these limitations also provide directions for future research: (1) This study employed self-reported questionnaires to collect data. Although reverse-coded items and anonymous responses were used to reduce common method bias, the data may still be influenced by social desirability effects and subjective errors, potentially affecting the conclusions. Future research may consider integrating multiple data sources, such as behavioral tracking, third-party evaluations, or laboratory measurements, to enhance the objectivity and reliability of the data. (2) Due to the cross-sectional design of this study, causal relationships and long-term effects among variables cannot be determined. Future studies could adopt longitudinal surveys or experimental designs to further explore the dynamic effects of gender stereotypes on women's physical activity. (3) The mediating mechanisms between gender stereotypes and female exercise behavior, aside from psychological need satisfaction in exercise and negative exercise emotions, may also include other factors, such as exercise commitment, self-efficacy, and stress perception, all of which have been shown to mediate the relationship between social cognition and exercise behavior. Future research should further consider a broader range of variables to provide comprehensive insights and references for understanding the antecedent mechanisms of female exercise behavior. (4) Given the constraints on questionnaire length and concerns over participant privacy, key control variables such as body mass index (BMI) and occupation were not included in the present study, which may have limited the explanatory power of the model. Future research could incorporate these variables under more comprehensive data collection conditions to enhance the robustness and generalizability of the findings. (5) Although this study focused on context-specific stereotypes, it did not address broader societal gender stereotypes. This may limit a more comprehensive understanding of gender stereotypes as a general sociopsychological mechanism. Future research could consider employing more inclusive measures of gender stereotypes.

## Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

## Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the [patients/participants OR patients/participants legal guardian/next of kin] was not required to participate in this study in accordance with the national legislation and the institutional requirements.

## Author contributions

KG: Data curation, Investigation, Writing – original draft, Writing – review & editing. QH: Conceptualization, Writing – review & editing.

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The 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.

## Generative AI statement

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# Built environment effects on the physical activity and mental well-being of young women in the Balkans

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**Introduction:** While physical activity is widely recognized as a key factor in physical and mental health, the impact of subjective and objective built environment characteristics on well-being across different population groups remains understudied. This gap is particularly evident among specific ethnic groups and genders, as most such studies focus on populations from Western and high-income countries. The primary objective of this paper is to assess the associations between various built environment characteristics, including both objective and subjective features, with the levels of physical activity and the well-being of young women in the Balkans.

**Methods:** To achieve this, a questionnaire survey was designed and implemented in five cities in the Balkans: Niš (Serbia), Plovdiv (Bulgaria), Athens (Greece), Bucharest (Romania), and Štip (North Macedonia), targeting the sub-population of young women. Multiple Linear Regression (MLR) modelling was employed to identify the subjective and objective built environment characteristics that affect engagement in moderate and vigorous physical activity and well-being.

**Results:** Findings of this paper show that a high level of street connectivity is associated with a higher level of moderate and vigorous physical activity. Additionally, there is a significant association between exciting green spaces in the neighborhood, proximity to shops, mixed land-use neighborhoods, cycling infrastructure, and higher levels of physical activity and well-being.

**Discussion:** These results suggest that inclusive urban planning strategies could play a key role in improving public health outcomes for this underrepresented demographic.

KEYWORDS

**built environment, physical activity, mental well-being, young women, Balkan countries**

# 1 Introduction

Physical activity (PA) comprises a key factor in promoting well-being, regardless of age, gender, or nationality, with well-being being strongly correlated with physical, mental and psychological health conditions (Marco et al., 2005; Haskell et al., 2007; Mahindru et al., 2023). Numerous studies exploring the association between women's PA and mental well-being can be found in international literature, with their results indicating a positive correlation of PA and well-being (Brehm and Iannotta, 1998; Molina-García et al., 2011; Staurowsky et al., 2015). At the same time, diverse populations may experience disparities in access to or engagement with physical activities (Saffer et al., 2013). Women, in particular, tend to engage in less PA than men, due to various exogenous but also gender-based factors. This issue is particularly significant for young women, as it not only shapes their present well-being, but it may also have long-term implications. Mayo et al. (2020) noted that establishing healthy routines at a young age increases the likelihood that they will be maintained throughout life.

While various age groups are considered in the relevant studies, the most explored ones are students, middle-aged and older women, while studies on young women (e.g., 26–40 years) are less frequent. The present study focuses on young women aged between 17 and 40 years of age. The reason for selecting this particular age group is that it is closely linked to many gender-specific factors that can significantly influence PA and mental well-being. These factors include major transitions in daily routines (such as daily commuting routines from school to university, from university to work, or directly from school to work), stress from relationships, childbirth, domestic violence, low socioeconomic status, poverty, concerns about weight and body image, and the challenge of balancing parental and work responsibilities (O'Leary and Helgeson, 1997).

One of the key contributing factors of physical activity levels, and hence well-being is an individual's surroundings, often referred to as the built environment (McCormack and Shiell, 2011). The influence of the built environment affects several types of physical activity: home-based PA, occupational or work-related PA, travel PA, and leisure time PA (Elshahat et al., 2020). Built environment elements affecting active travel, i.e., walking or cycling for utilitarian or recreational purposes, include the design characteristics of pedestrian or cyclist infrastructure (availability, quality, connectivity, safety), the surrounding environment (open spaces, landscape aesthetics, security, lighting, buildings' height, cleanliness) and the neighborhood design (distance to several destinations, land use mix, interaction of the different transportation mode networks) (Pearce and Maddison, 2011). In particular, factors that contribute to improved PA and well-being, specifically regarding walking and cycling infrastructure, include access to sidewalks, walking or cycling paths, walkways or cycleways, biking facilities such as parking stations and shared bike systems, as well as high-quality surfaces, increased connectivity, and safe crossing sections (such as enhanced traffic signage, bridges, and underpasses). These elements make walking and cycling more appealing, thus promoting travel-related PA. An additional element affecting the level of PA is landscape characteristics. Walking or cycling is more appealing in aesthetically pleasing environments, water-related features (such as lakes, rivers, seas, and fountains), landmarks, and in areas with clean infrastructure, good air quality, attractive buildings, green and open spaces, and low noise levels. Safety and security are particularly significant elements, the deterioration of which may hinder PA, especially for young women. Conversely, well-lit areas, areas with low crime rates and enhanced road safety increase the propensity for PA. Last, additional elements such as land use diversity, short distances to reach different destinations, proximity to public transport stations, proximity to parks with gym facilities, and neighborhoods with strong social bonds that foster social interaction usually affect positively PA levels. The relationship between built environment characteristics and physical activity and mental health is understudied, particularly among residents of Eastern Europe and Balkan countries, as well as among specific population groups such as women. Although several studies have assessed the associations between urban design, neighborhood characteristics, and PA or active mobility (such as cycling and walking), most of this research has focused on high-income and Western European countries. Social, economic, and cultural differences may significantly influence the relationship between built environment features and physical activity or mental health in different regions. Sallis et al. (2016) examined the associations between physical activity and urban environment features in 14 cities worldwide; however, only two cities from Eastern Europe; Olomouc and Hradec Králové in the Czech Republic were included in the study. Another study assessed the relationship between the physical environment and the domains of PA among European adults using a systematic literature review. According to that study, there is an imbalance in the findings between Western and Eastern Europe, as most of the existing knowledge in this area comes from Western European countries (Holle et al., 2012). Most studies exploring the effect of the built environment on PA are based on cases from Western and Northern Europe, the US, Australia, as well as some middle and low-income countries (Bassett et al., 2008; Oyeyemi et al., 2011; Elshahat et al., 2020). Few studies, however, focus on Balkan countries, where the populations exhibit different characteristics, socioeconomic status and mentalities compared to those of the aforementioned regions, while also being highly car-dependent. The Balkans suffer from inadequate infrastructure for pedestrians and cyclists, while at the same time, various additional elements of the built environment may discourage PA, particularly among women (Pojani et al., 2017). To address this gap, the present study focuses on five cities in Balkan countries. The contribution of this study is to assess the correlation between built environment characteristics and PA, mental health among a less-study group: women in Balkan countries.

Physical activity (PA) can be measured using several indices, including intensity (light, moderate, or vigorous), duration, frequency, type (e.g., aerobic, strength training), and volume, which combines intensity, frequency, and duration, and other, less commonly used indices. Well-being on the other hand is a more abstract term, which can be measured by several different standardized questionnaires including the General Health Questionnaire, GHQ (Goldberg, 1978), the Affectometer (Kammann and Flett, 1983), the Beck Depression Inventory (BDI) (Beck et al., 1987), the Health Questionnaire for Adults (HQA) the Medical Outcomes Study (MOS), the MOS Short-Form General Health Survey, the Gothenburg Quality of Life Instrument (GQL) (Tibblin et al., 1990), the Rosenberg Self-Esteem Scale (Rosenberg, 2015), and the Subjective Vitality Scale (Ryan and Frederick, 1997). In this study, PA will be measured through intensity, frequency and duration, and mental well-being will be computed using the Warwick-Edinburgh scale (WEMWBS) which represents the perceived mental well-being (Stewart-Brown et al., 2011).

The objective of this study is to determine the impact of various built environment characteristics on PA levels and perceived mental well-being in Balkan countries, with a focus on young women. This objective will be addressed by answering the following research questions (RQ):

> *RQ1*: Does the built environmental affect moderate and vigorous PA of young women in the Balkan countries, and how?
>
> *RQ2*: Does the built environmental affect young women's mental well-being in the Balkans countries, and how?

# 2 Methodology

## 2.1 Case cities

For the needs of this study, five cities from different Balkan countries were selected for the questionnaire survey. These are Niš (Serbia), Plovdiv (Bulgaria), Athens (Greece), Bucharest (Romania) and Štip (North Macedonia). The selected cities vary in size, built environment characteristics and dedicated pedestrian and cyclist infrastructure.

Niš is the largest city and industrial center in the south-east of Serbia, with a population of around 250,000 citizens which also makes it the third largest city in the country. The private car still comprises the dominant transport mode. The public transport network primarily relies on buses. Dedicated infrastructure for walking and cycling has not been a priority for the city so far.

Plovdiv is the second largest city in Bulgaria with a population of 348,000 inhabitants, 52% of which are women. Plovdiv boasts the most extensive cycling network, which is continuously expanded to further promote the use of active transport modes. The total length of the cycle lanes is 60 km, covering 58.8% of the city's area. Additional factors including the wrongly positioned bus stops and the ongoing infrastructure reconstruction activities, also hinder cycling continuity.

Athens, the capital of Greece, has an urban population of 3,059,764 and a metropolitan population of 3,638,281 inhabitants, making it the largest city of the country. Athens is a major transportation hub and has an extended public transport network that serves the city and its metropolitan area. The Athenian metro is the most reliable public transport mode. In addition, trips are served by a tram and an extensive bus network, but their performance is affected by traffic congestion. Although sustainable transport options are offered, Athenians comprise a car-dependent population, with the proportion of more than 50% of the total trips made by private car. In general, the quality of pedestrian infrastructure is poor with narrow or even non-existent sidewalks, obstacles on them (ranging from kiosks and restaurant seats to parked vehicles) and bad surface conditions. Considering the cycling network, its quality is even worse.

Bucharest, the capital of Romania, is a vibrant metropolis with a population of approximately 2 million residents, making it the largest city in the country. Public transportation is widely used, with an extensive network of buses, trams, and the metro system facilitating daily commutes for over 1.2 million people. Active mobility is also on the rise, with increased investments in cycling infrastructure and pedestrian zones, including over 25 km of dedicated cycle lanes. Despite these improvements, walking and cycling rates remain lower than the EU average, with only about 5% of trips made by bicycle and 10% by walking, compared to the EU averages of 8 and 12%, respectively.

Štip is the smallest participating city with 44,866 inhabitants. The city is located in the eastern part of the Republic of North Macedonia and is the 7th largest city in the country. The city is connected to its suburbs and neighboring municipalities through a bus network, and its pedestrian and cycling infrastructure spans approximately 7 km. The terrain in Štip is diverse, with flat areas along the Bregalnica and Otinja rivers, and hilly regions in other parts of the city. On the other hand, hilly terrains in some city areas reduce the uptake of active transport modes. For example, cycling, as a recreational activity, is popular around the fortress Isar or the Štip Kale. However, reaching the city's most famous landmark requires climbing more than 400 stairs.

## 2.2 Questionnaire design

A questionnaire survey was designed to identify knowledge gaps regarding physical activity, mental well-being, and the built environment in the Balkans region. The tool used was a revealed preference questionnaire, which was designed following a mixed-methods approach, incorporating both quantitative and qualitative questions. The questionnaire was divided into five sections: "Neighborhood and Mobility Attributes," "Physical Activity," "Nutrition," "Well-being," and "Socioeconomic Factors."

Data on mobility attributes was collected through questions revealing participants' modal choice preferences. Data on neighborhood attributes is classified into two categories: perceived attributes and objective characteristics of the built environment. The perceived attributes were collected utilizing the ALPHA environmental questionnaire (Spittaels et al., 2009). This involves a standardized set of questions addressing various elements of the neighborhood environment such as land uses, walking and cycling infrastructure, prevailing conditions including safety and security and so on. To explore the objective built-environment elements, participants were asked to indicate the nearest intersection or landmark to their home [their exact home address inquired, in accordance with the General Data Protection Regulation (GDPR)]. Objective built environment variables, such as link density, street-length density, intersection density, and link-node ratio, were calculated within a 600-meter catchment area utilizing GIS software. The physical activity level of the participants was estimated using the short form of the International Physical Activity Questionnaires (IPAQ) (Lee et al., 2011). Through IPAQ self–reported physical levels and attributes of engagement in moderate and vigorous PA, including the number of days and time (minutes) spent for walking, sitting, and screen time are recorded. Furthermore, three questions on eating habits provided data on participants' nutrition. Participant well-being was measured using the Warwick-Edinburg Mental Well-Being Scale (WEMWBS). This scale is aimed at identifying the perceived mental well-being, through a set of 14 different statements referring to personal feelings and different aspects of well-being. Last, data regarding socioeconomic variables was collected in the last section of the questionnaire and included information on age, marital status, household size, number of children, work status, gross household income, financial status, and private transport mode ownership and accessibility.

The questionnaire was initially designed in English, while prior to being distributed in the five cities it was translated to the respective languages. A set of guidelines was also created for clarification reasons.

In total the questionnaire consisted of 49 questions, and participants required approximately 10–15 min to complete it.

## 2.3 Data collection

Data was collected over a three-month period, through on-line distribution. Online distribution included posts at various social media channels and groups, as well as to participants known to the interviewers or interviewees. Efforts were made to ensure a heterogeneous sample, including participants with diverse sociodemographic characteristics, to capture a wide range of perspectives. Participants who had difficulty understanding the questions were invited to an online meeting to receive additional information and guidance on how to answer them. As such, the sampling method comprised a combination of convenience, snowball and quota sampling methods. For the needs of the study, participant gender and age were predefined, i.e., participants had to be young women, aged between 17 and 40. The final sample consisted of 1,222 women, with their distribution across the different cities being 49% (597) from Bucharest, 17% (205) from Niš, 15% (135) from Athens, 11% (191) from Štip, and 8% (94) from Plovdiv.

The sample composition in total and per city is illustrated in Table 1.

As anticipated, the sociodemographic characteristics of the survey participants differ across the five cities/countries. In particular, the predominant age group varies across the pilot cities, with the sample concentrated in the 17–30 age range. Considering employment, the prevalent groups are students and women who work. Marital status is fairly evenly distributed across the different groups, while only a small proportion of women have children. Most women in the sample own a private car, and the majority report a middle-income financial status category.

## 2.4 Data processing

Following data collection, the responses provided in text format were first translated from the local languages into English. Two rounds of data cleaning and validation were then conducted to create a valid dataset. The next step involved variable coding, which was primarily required for categorical variables. The dependent variables were MPA, VPA and mental well-being, while the independent were the built environment and neighborhood subjective variables, the built environment objective variables and the different socioeconomic characteristics.

The index utilized to represent moderate and vigorous PA was calculated according to the guidelines of the short version of IPAQ, with the coefficients for moderate and vigorous PA being 4 and 8, respectively. The total Metabolic Equivalent of Task (MET) was calculated as the sum of MET-minutes per week from walking, moderate, and vigorous activities. The MET coefficients used were 3.3 for walking, 4.0 for moderate physical activity (MPA), and 8.0 for vigorous physical activity (VPA) based on IPAQ protocol. To estimate mental well-being index, the methodology reported in Stewart-Brown et al. (2011) was adopted. Participants rated different elements of their well-being utilizing a 5-point Likert scale for each question. The mental well-being index was then computed by summing the scores of all 14 questions for each participant. Figure 1 shows the different levels of MPA, VPA, and well-being among various countries included in this study. To compute the objective built environment parameters, GIS software (ArcMap 10.4) was used. Shapefiles from the pilot cities, i.e., Athens, Štip, Plovdiv, Bucharest, and Niš were downloaded from OpenStreetMap, and participants' "home" locations (indicated by the nearest intersection or landmark) were transferred from Google Maps to ArcMap. The disaggregated built environment variables, which were link, intersection, and street-length density, within a pre-defined catchment area were calculated in GIS using network and spatial analysis tools. The catchment area was defined as a 600-meter radius, measured along the street network, in accordance with urban transportation literature (Masoumi et al., 2019; Li et al., 2019).

## 2.5 Analysis methods

Kolmogorov–Smirnov and Sharipo-Wilk tests were applied for the assessment of the variable distributions, which would determine the statistical analysis that would be adopted. A $p$-value smaller than 0.05 suggests that the null hypothesis, which is that the variable follows a normal distribution, should be rejected. The computed $p$-values (Table 2) were below 0.05, hence the three dependent variables – namely, moderate and vigorous PA, and mental well-being among young women in the Balkans are not normally distributed.

Multiple linear regression (MLR) modelling was performed to identify the subjective and objective built environment and neighborhood factors that affect the engagement in moderate and vigorous PA, and the mental well-being of the sample, and provide answers to the study's research questions. The subjective built environment and neighborhood variables were derived from the questionnaire based on the perceptions and attitudes of participants reported in the relevant questionnaire section. These variables include the availability of different routes for cycling, the pleasantness of these routes, land use diversity, the pleasantness of the walking environment, the availability of green spaces and trees near pedestrian areas, shops in the neighborhood, and segregated cycling routes in the neighborhood. The objective built environment variables are the link-node ratio, link density, and street-length density, as specified in the previous section. However, only those exhibiting significant associations in the MLRs were kept in the final models.

To obtain better results, socioeconomic variables were treated as control variables in the MLR models. The control variables for MPA, as indicated from the statistical analysis, were age, household size, number of children, income, and employment status. Additionally, age, household size, number of children, and income were the control variables in the VPA model. Finally, the only controlled variable in the MLR for mental well-being was income. Different socioeconomic variables were fixed in the multiple linear regression (MLR) models to achieve the best results, characterized by the highest R-squared value, more significant independent variables, and statistically significant control variables.

# 3 Results

## 3.1 Descriptive statistical analysis

The five pilot cities exhibited variations in the objective built environment characteristics, which also represent street connectivity. Higher values of link density, link-node ratio, and intersection density

TABLE 1 Distribution of socioeconomic characteristics.

| Variable | Category | Measure | Country | | | | | Total |
|---|---|---|---|---|---|---|---|---|
| | | | Greece | Bulgaria | Romania | Serbia | North Macedonia | |
| Participants | Country | N/% | 135 (11%) | 94 (8%) | 597 (49%) | 205 (17%) | 191 (15%) | 1,222 |
| Participants per age | 17–20y | N/% | 11 (8%) | 15 (16%) | 484 (81%) | 0 (0%) | 92 (48%) | 602 (49%) |
| | 21–25 y | N/% | 68 (50%) | 45 (48%) | 48 (8%) | 58 (28%) | 66 (35%) | 285 (23%) |
| | 26–30 y | N/% | 55 (41%) | 33 (35%) | 63 (11%) | 147 (72%) | 33 (17%) | 331 (27%) |
| | 31–38 y | N/% | 1 (1%) | 1 (1%) | 2 (0.3%) | 0 (0%) | 0 (0%) | 4 (0.3%) |
| | Total | N/% | 135 (11%) | 94 (7.7%) | 597 (48.9%) | 205 (16.8%) | 191 (15.6%) | 1,222 |
| Employment and work status | In paid work (or away temporarily) (employee, self-employed, working for your family business) | N/% | 71 (52.6%) | 55 (58.5%) | 96 (16.1%) | 205 (100.0%) | 44 (23.0%) | 471 (38.5%) |
| | Unemployed and actively looking for a job | N/% | 8 (5.9%) | 5 (5.3%) | 6 (1%) | 0 (0%) | 12 (6.3%) | 31 (2.5%) |
| | Permanently sick or disabled | N/% | 1 (0.7%) | 0 (0%) | 0 (0%) | 0 (0%) | 0 (0%) | 1 (0.1%) |
| | Doing housework, looking after children or other persons | N/% | 2 (1.5%) | 0 (0%) | 5 (0.8%) | 0 (0%) | 6 (3.1%) | 13 (1.1%) |
| | Student | N/% | 53 (39.3%) | 34 (36.2%) | 490 (82.1%) | 0 (0%) | 129 (67.5%) | 706 (57.8%) |
| | Total | N/% | 135 (11%) | 94 (7.7%) | 597 (48.9%) | 205 (16.8%) | 191 (15.6%) | 1,222 |
| Marital status | Single/divorced/widow | N/% | 57 (42.2%) | 46 (48.9%) | 282 (47.2%) | 89 (43.4%) | 87 (45.5%) | 561 (45.9%) |
| | Married/living with my partner | N/% | 19 (14.1%) | 25 (26.6%) | 86 (14.4%) | 116 (56.6%) | 34 (17.8%) | 280 (22.9%) |
| | In a relationship but living separately | N/% | 59 (43.7%) | 23 (24.5%) | 229 (38.4%) | 0 (0%) | 70 (36.6%) | 381 (31.2%) |
| | Total | N/% | 135 (11%) | 94 (7.7%) | 597 (48.9%) | 205 (16.8%) | 191 (15.6%) | 1,222 |
| Number of children in the household | 0 | N/% | 133 (99%) | 89 (95%) | 550 (92%) | 48 (23%) | 159 (84%) | 979 (80%) |
| | 1 | N/% | 2 (1%) | 4 (4%) | 27 (5%) | 66 (32%) | 14 (7%) | 113 (9%) |
| | 2 | N/% | 0 (0%) | 1 (0.01%) | 15 (3%) | 91 (44%) | 14 (7%) | 121 (10%) |
| | 3 | N/% | 0 (0%) | 0 (0%) | 5 (1%) | 0 (0%) | 2 (1%) | 7 (1%) |
| | 4 | N/% | 0 (0%) | 0 (0%) | 0 (0%) | 0 (0%) | 1 (1%) | 1 (1%) |
| | Total | N/% | 135 (11%) | 94 (7.7%) | 597 (48.9%) | 205 (16.8%) | 191 (15.6%) | 1,221 |
| Car ownership | No | N/% | 53 (39.3%) | 39 (41.5%) | 189 (31.7%) | 0 (0%) | 68 (35.6%) | 349 (28.6%) |
| | Yes | N/% | 82 (60.7%) | 55 (58.5%) | 408 (68.3%) | 203 (100%) | 123 (64.4%) | 871 (71.4%) |
| | Total | N/% | 135 (11%) | 94 (7.7%) | 597 (49%) | 203 (16.7%) | 191 (15.6%) | 1,220 |

*(Continued)*

TABLE 1 (Continued)

| Variable | Category | Measure | Country | | | | | Total |
|---|---|---|---|---|---|---|---|---|
| | | | Greece | Bulgaria | Romania | Serbia | North Macedonia | |
| Gross household monthly income | 0 | N/% | 8 (5.9%) | 1 (1.1%) | 45 (7.5%) | | 84 (44%) | 138 (13.6%) |
| | 0–499 | N/% | 9 (6.7%) | 10 (10.8%) | 59 (9.9%) | | 52 (27.2%%) | 130 (12.8%) |
| | 500–999 | N/% | 19 (14.1%) | 27 (29%) | 91 (15.2%) | | 35 (18.3%) | 172 (16.9%) |
| | 1,000–1,499 | N/% | 28 (20.7%) | 22 (23.7%) | 110 (18.4%) | | 5 (2.6%) | 165 (16.2%) |
| | 1,499–1999 | N/% | 20 (14.8%) | 15 (16.1%) | 80 (13.4%) | | 2 (1%) | 117 (11.5%) |
| | 2000–2,499 | N/% | 16 (11.9%) | 13 (14%) | 79 (13.2%) | | 2 (1%) | 110 (10.8%) |
| | 2,500–2,999 | N/% | 20 (14.8%) | 4 (4.3%) | 31 (5.2%) | | 1 (0.5%) | 56 (5.5%) |
| | 3,000–3,499 | N/% | 13 (9.6%) | 1 (1.1%) | 24 (4%) | | 2 (1%) | 40 (3.9%) |
| | 3,500 and more | N/% | 2 (1.5%) | 0 (0%) | 78 (13.1%) | | 8 (4.2%) | 88 (8.7%) |
| | Total | | 135 (13.3%) | 93 (9.2%) | 597 (58.7%) | | 191 (18.8%) | 1,016 |
| Financial status | Low | N/% | 20 (14.8%) | 3 (3.2%) | 17 (2.8%) | | 27 (14.1%) | 67 (6.6%) |
| | Low-mid | N/% | 24 (17.8%) | 27 (28.7%) | 38 (6.4%) | | 31 (16.2%) | 120 (11.8%) |
| | Mid | N/% | 70 (51.9%) | 52 (55.3%) | 373 (62.5%) | | 104 (54.5%) | 599 (58.9%) |
| | Mid-high | N/% | 21 (15.6%) | 12 (12.8%) | 139 (23.3%) | | 24 (12.6%) | 196 (19.3%) |
| | High | N/% | 0 (0%) | 0 (0%) | 30 (5%) | | 5 (2.6%) | 35 (3.4%) |
| | Total | N/% | 135 (13.3%) | 94 (9.2%) | 597 (58.7%) | | 191 (18.8%) | 1,017 |

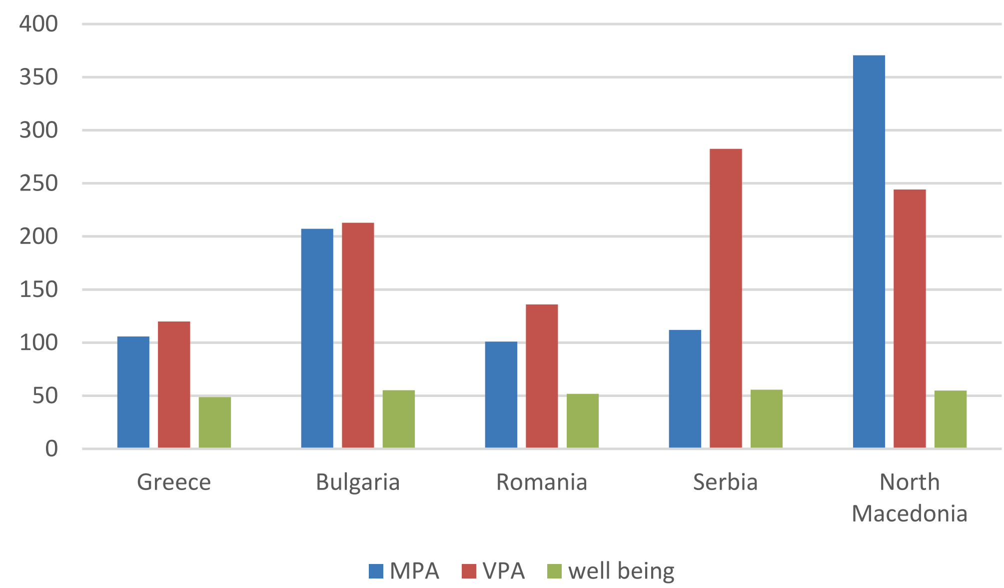


FIGURE 1
MPA, VPA and well-being scores.

are associated with greater street connectivity in the neighborhood. The average link-node ratios were found to be 2.859, 1.476, 1.741, 1.743, and 2.553 for Athens, Bucharest, Niš, Plodiv and Štip, respectively.

MPA and VPA present distinct patterns and mean values across the different countries. In particular, the distribution between MPA and VPA is rather similar in the explored cities in Greece, Bulgaria and Romania. In contrast, participants from Serbia engage in substantially more VPA than MPA, while women from North Macedonia engage in more MPA than VPA. Despite variations in MPA and VPA levels across countries, the average mental well-being score remains relatively consistent, ranging from approximately 49–56 (Table 3).

To explore the differences of MPA, VPA and mental well-being between countries, the Kruskal-Wallis test was performed. Tables 2, 4, 5, illustrate the results.

Results indicate that almost all pairwise comparisons show statistically significant differences considering MPA and VPA. These are reflected in Tables 2, 4, where $p$-values exhibit values equal or lower than 0.05. Moreover, although the differences of the mental well-being scores across the five cities were relatively small, the statistical analysis suggests that these differences are statistically significant for most pair-wise comparisons (Table 5).

## 3.2 MLR model for MPA and VPA

Two MLR models were developed separately for MPA and VPA. Table 6 summarizes the MPA model and the related ANOVA F-test. Most of the socioeconomic variables (age, household size, number of children, gross household monthly income, and employment status) affect MPA, however, as the aim of the study is to isolate the effect of the built environment on MPA, we treat them as control variables, and their effect is not elaborated in the present study. The only objective built environment variable in the model is street-length density, which is marginally significant ($p = 0.097$). It is positively correlated with MPA, suggesting that street connectivity increases the MPA levels of young women. Two subjective built environment variables were found to significantly affect MPA. The availability of shops near the living place presents an 8% reduction in MPA probably because shopping, i.e., walking around the shops is

TABLE 2 Kuskul-Wallis test for country-wide comparison of MPA levels.

| Country 1 vs. Country 2 | Test statistic | Std. error | Std. test statistic | P |
|---|---|---|---|---|
| Greece–Romania | −5.557 | 33.157 | −0.168 | 0.867 |
| Greece–Serbia | −99.565 | 38.563 | −2.582 | 0.010 |
| Greece–North Macedonia | −149.438 | 39.120 | −3.820 | <0.001 |
| Greece–Bulgaria | −192.053 | 46.737 | −4.109 | <0.001 |
| Romania–Serbia | −94.009 | 28.164 | −3.338 | 0.001 |
| Romania–North Macedonia | −143.882 | 28.922 | −4.975 | <0.001 |
| Romania–Bulgaria | 186.497 | 38.606 | 4.831 | <0.001 |
| Serbia–North Macedonia | −49.873 | 34.989 | −1.425 | 0.154 |
| Serbia–Bulgaria | 92.488 | 43.338 | 2.134 | 0.033 |
| North Macedonia–Bulgaria | 42.615 | 43.834 | 0.972 | 0.331 |

TABLE 3 Descriptive statistics for MPA, VPA, and mental well-being.

| Country | Variable | N | Min | Max | Mean | Std. deviation |
|---|---|---|---|---|---|---|
| Greece | MPA (min/week) | 135 | 0 | 1,680 | 105.90 | 202.720 |
| | VPA (min/week) | 135 | 0 | 840 | 119.95 | 159.143 |
| | Well-being | 135 | 27 | 70 | 48.66 | 10.097 |
| Bulgaria | MPA (min/week) | 94 | 0 | 1,500 | 207.14 | 266.907 |
| | VPA (min/week) | 92 | 0 | 2,100 | 212.90 | 291.600 |
| | Well-being | 94 | 26 | 70 | 55.28 | 8.982 |
| Romania | MPA (min/week) | 597 | 0 | 1,440 | 100.91 | 160.436 |
| | VPA (min/week) | 597 | 0 | 2,520 | 136.03 | 220.545 |
| | Well-being | 597 | 14 | 70 | 51.78 | 10.188 |
| Serbia | MPA (min/week) | 205 | 0 | 420 | 112.05 | 91.515 |
| | VPA (min/week) | 205 | 120 | 800 | 282.54 | 133.554 |
| | Well-being | 205 | 52 | 62 | 55.71 | 3.037 |
| North Macedonia | MPA (min/week) | 191 | 0 | 3,360 | 370.58 | 621.042 |
| | VPA (min/week) | 191 | 0 | 1800 | 244.27 | 357.129 |
| | Well-being | 191 | 30 | 70 | 54.82 | 8.956 |

TABLE 4 Kuskul-Wallis test for country-wide comparison of VPA levels.

| Country 1 vs. Country 2 | Test statistic | Std. error | Std. test statistic | *P* |
|---|---|---|---|---|
| Greece–Romania | −5.449 | 33.216 | −0.164 | 0.870 |
| Greece–North Macedonia | −104.875 | 39.190 | −2.676 | 0.007 |
| Greece–Bulgaria | −141.250 | 47.119 | −2.998 | 0.003 |
| Greece–Serbia | −381.826 | 38.631 | −9.884 | <0.001 |
| Romania–North Macedonia | −99.426 | 28.974 | −3.432 | 0.001 |
| Romania–Bulgaria | 135.800 | 39.037 | 3.479 | 0.001 |
| Romania–Serbia | −376.377 | 28.214 | −13.340 | <0.001 |
| North Macedonia–Bulgaria | 36.374 | 44.231 | 0.822 | 0.411 |
| North Macedonia–Serbia | 276.950 | 35.051 | 7.901 | <0.001 |
| Bulgaria–Serbia | −240.576 | 43.737 | −5.500 | <0.001 |

TABLE 5 Kuskul-Wallis test for country-wide comparison of mental well-being.

| Country 1 vs. Country 2 | Test statistic | Std. error | Std. test statistic | *P* |
|---|---|---|---|---|
| Greece–Romania | −111.870 | 33.605 | −3.329 | 0.001 |
| Greece–North Macedonia | −229.163 | 39.649 | −5.780 | <0.001 |
| Greece–Bulgaria | −241.367 | 47.369 | −5.096 | <0.001 |
| Greece–Serbia | −264.085 | 39.084 | −6.757 | <0.001 |
| Romania–North Macedonia | −117.293 | 29.313 | −4.001 | <0.001 |
| Romania–Bulgaria | 129.497 | 39.128 | 3.310 | 0.001 |
| Romania–Serbia | −152.215 | 28.545 | −5.332 | <0.001 |
| North Macedonia–Bulgaria | 12.205 | 44.427 | 0.275 | 0.784 |
| North Macedonia–Serbia | 34.922 | 35.462 | 0.985 | 0.325 |
| Bulgaria–Serbia | −22.717 | 43.924 | −0.517 | 0.605 |

TABLE 6 MLR model for MPA ($R^2 = 0.054$).

| Variable group | Independent variable | B | Std. error | $\beta$ | *t* | *P* | VIF |
|---|---|---|---|---|---|---|---|
| Constant | | 569.130 | 153.52 | | 3.707 | <0.001 | |
| Control | Age | −4.914 | 3.19 | −0.059 | −1.543 | 0.123 | 1.264 |
| | Household Size | 28.028 | 7.25 | 0.135 | 3.866 | <0.001 | 1.053 |
| | Number of children | 55.651 | 25.05 | 0.084 | 2.222 | 0.027 | 1.253 |
| | Gross household monthly income | −51.913 | 23.89 | −0.074 | −2.173 | 0.030 | 1.017 |
| | Employment and work status | −135.107 | 52.59 | −0.089 | −2.569 | 0.010 | 1.039 |
| Objective built environment | Street-length density | 163.927 | 98.74 | 0.057 | 1.660 | 0.097 | 1.014 |
| Subjective built environment | Availability of shops in the neighborhood | −71.074 | 29.41 | −0.084 | −2.417 | 0.016 | 1.056 |
| | Availability of many routes for cycling in the neighborhood | 56.445 | 23.92 | 0.082 | 2.360 | 0.019 | 1.038 |

| ANOVA *F*-test | | | | |
|---|---|---|---|---|
| Sum of squares | df | Mean square | *F* | *P* |
| 5,024,421 | 8 | 628,053 | 6.678 | <0.001 |

TABLE 7 MLR model for VPA ($R^2 = 0.062$).

| Variable group | Independent variable | B | Std. error | *Beta* | *t* | *P* | VIF |
|---|---|---|---|---|---|---|---|
| Control | Age | −2.892 | 2.666 | −0.043 | −1.085 | 0.278 | 1.278 |
| | Household Size | 18.181 | 6.070 | 0.107 | 2.995 | 0.003 | 1.048 |
| | Number of children | −37.966 | 22.140 | −0.068 | −1.715 | 0.087 | 1.278 |
| | Gross household monthly income | −24.941 | 19.668 | −0.045 | −1.268 | 0.205 | 1.013 |
| Objective built environment | Link density | −25278.217 | 7762.613 | −0.123 | −3.256 | 0.001 | 1.160 |
| | Link-node ratio | 10.795 | 5.311 | 0.076 | 2.033 | 0.042 | 1.156 |
| Subjective built environment | Availability of shops in the neighborhood | −41.562 | 24.399 | −0.061 | −1.703 | 0.089 | 1.055 |
| | Availability of many routes for cycling in the neighborhood | 56.273 | 17.843 | 0.111 | 3.154 | 0.002 | 1.016 |

| ANOVA *F*-test | | | | |
|---|---|---|---|---|
| Sum of squares | df | Mean square | *F* | *P* |
| 2,674,066 | 8 | 334,258 | 5 | <0.001 |

associated more with light PA rather than MPA ($p = 0.016$). Moreover, the presence of biking routes in the living neighborhood is, as expected, positively correlated with MPA, and is associated with 8% more MPA among the respondents of this study ($p = 0.019$). It should be noted that there is no multicollinearity among the model's independent variables, as the VIF values ranged between 1 and 1.3. The ANOVA F-test results indicate that the model is valid ($p < 0.001$).

Table 7 presents the MLR model for VPA. In the case of vigorous PA, there is a smaller number of socioeconomic factors that affect the variable levels. These are age, household size, number of children, and gross household monthly income, and were treated again as control variables. Two objective built environment variables, those of link density and link-node ratio were found to be significant in the model ($p = 0.001$ and $p = 0.042$, respectively). Both represent street network connectivity and both show that there is a positive relationship between connectivity and VPA. When link density, which is represented by ratio of intersections to the area, increases VPA also increases among the respondents. As the link-node ratio increases, represented by the ratio of the number of streets to the number of intersections, both connectivity and vigorous physical activity (VPA) decrease. Moreover, specific subjective built environment variables appear to affect VPA. These are the availability of shops in the neighborhood and the availability of biking routes. Availability of shops in the neighborhood is associated with 6% lower VPA among the respondents ($p = 0.089$). On the other hand, availability of cycling routes in the neighborhood is significantly correlated with 11% more VPA ($p = 0.002$). The model is valid as the *p*-value of the ANOVA F test is <0.001. The model has an $R^2$ of 6% and there is no collinearity between the independent variables, as the VIF values are between 1 and 1.3.

## 3.3 MLR model for mental well-being

MLR modelling was employed to analyse the associations between built environment variables and mental well-being. The respondents' well-being scores were treated as the dependent variable. The model achieved the best fit by treating gross household and monthly income as control variables. Five subjective built environment factors were identified as having an impact on mental well-being levels, while objective built environment variables related to street network were not found to be influential (Table 8).

The availability of cycling routes in the neighborhood is strongly correlated with perceived well-being ($p < 0.001$). The correlation is positive, and the model results show that the availability of biking routes in the neighborhood is associated with a 12% higher well-being score. The diversity of land use, reflecting the presence of different urban functions in the living neighborhood, is significantly and positively associated with perceived well-being ($p = 0.006$). This indicates that a diverse land-use environment results in an 8.5% higher well-being score, particularly among women. The attractiveness of cycling routes and their surrounding environment is marginally positively correlated with well-being ($p = 0.072$), with a 7% increase in mental well-being associated with more attractive cycling routes. Similarly, the attractiveness of the neighborhood for walking comprises yet another significant independent variable ($p = 0.009$). Its positive coefficient indicates that the attractiveness of the area for walking results to a 10% increase in mental well-being among the respondents. Finally, the presence of green areas and trees in the neighborhood shows a marginally significant association with mental well-being ($p = 0.077$), corresponding to a 6% increase in the reported well-being. The *p*-value of the ANOVA F-test is below 0.001, indicating model validity. $R^2$ is 7.8%, meaning that the independent variables in the model explain 7.8% of the variation in the mental well-being of young women. As seen in Table 8, there is no sign of multicollinearity among the independent variables, as the VIF values range from 1 to 1.5.

# 4 Discussion

The present study provides valuable insights into how built environment characteristics influence physical activity (PA) and

TABLE 8 MLR model for mental well-being ($R^2 = 0.078$).

| Variable group | Independent variable | *B* | Std. error | *Beta* | *t* | *P* | VIF |
|---|---|---|---|---|---|---|---|
| Constant | | 39.434 | 1.941 | | 20.312 | <0.001 | |
| Control | Gross household monthly income | −1.281 | 0.671 | −0.058 | −1.910 | 0.056 | 1.006 |
| Subjective built environment | Availability of shops in the neighborhood | 2.687 | 0.709 | 0.123 | 3.791 | <0.001 | 1.156 |
| | Presence of diverse land use in the area | 1.776 | 0.649 | 0.085 | 2.736 | 0.006 | 1.052 |
| | Pleasance and attractiveness of the cycling routes | 1.328 | 0.737 | 0.066 | 1.802 | 0.072 | 1.470 |
| | Pleasance of the local neighborhood for walking | 2.119 | 0.807 | 0.096 | 2.628 | 0.009 | 1.464 |
| | Availability of green or trees along the streets in the neighborhood | 1.365 | 0.771 | 0.059 | 1.770 | 0.077 | 1.194 |

| ANOVA *F*-test | | | | |
|---|---|---|---|---|
| Sum of squares | df | Mean square | *F* | *P* |
| 7,939 | 6 | 1323.2 | 14.183 | <0.001 |

well-being in young women across five cities in the Balkans. International research suggests that the PA levels in females are lower than in males and presents a consistent decline throughout their lifespan (Guthold et al., 2018). The investigated age group of women (i.e., 17–40 year old) is unique in terms of their PA levels and well-being due to several age-specific events. As confirmed by study results, participants from different countries present different PA levels and different self-perceptions of their well-being. Statistical findings reveal significant cross-country differences in both moderate physical activity and vigorous physical activity. Women in North Macedonia report the highest MPA, followed by women from Bulgaria, while Romania reports lowest. Similar patterns are observed for VPA, with Serbia and North Macedonia leading in participation, while the lowest mean scores are reported for Romania and Greece. The low results for MPA and VPA for Romania and Greece are also confirmed in Sport and Physical Activity - Eurobarometer Survey (2022), WHO PA Fact Sheets for EU countries WHO (2021), and review studies from EU countries (Gerovasili et al., 2015). The lower PA levels in women are not only a result of biological factors, but are also influenced by societal expectations and cultural norms, which are more pronounced considering women in the target age group, thus exhibiting a higher effect (Peng et al., 2023). Changes in societal roles, for example enrolling in university, starting work, marriage, and motherhood are directly related to income, available free time, and setting life priorities. At the same time, these factors are closely associated with motivation for PA and the time available for it. As such, they can significantly impact the PA levels and movement habits of women. Several studies report that work (Winpenny et al., 2020), marriage, and childbirth (Brown et al., 2009; Gropper et al., 2020) as leading reasons for the decrease in the PA levels among young women. The participants in our study were quite diverse in terms of socioeconomic status, especially regarding employment and marital status. In particular, the majority of participants from Romania and North Macedonia were students, while participants from Greece, Bulgaria, and Serbia were employed. The variation in employment rates and student status across countries (e.g., 100% employment in Serbia vs. 16.1% in Romania) presents significant socioeconomic disparities. Previous research has shown that employment status and economic security are crucial determinants of PA levels, particularly in women (Bauman et al., 2012). Lower employment rates among participants from Romania may correlate with lower PA engagement due to financial constraints, limited access to recreational facilities, or psychological stress. As confirmed by Beenackers et al. (2012), in their review regarding different EU countries, higher socioeconomic status is associated with higher PA levels, particularly VPA during leisure time. At the same time, having a job, especially for married women with children, may result in a lack of free time, reducing the potential or the time spent for PA.

While finding time to engage in PAs is the key to being active, the way - HOW to do it or WHAT to do - and the location - WHERE to do it - can vary, affecting its feasibility, and hence its frequency and duration. Regarding the "HOW" dimension of PA, a wide range of activities are available including low and high-intensity activities, strength-oriented or cardio-oriented activities. The list of activities is long, and it can include walking, running, cycling, tennis, table tennis, swimming, ball sports, pilates, aerobics, HIIT, fitness, skying, yoga, tai–chi, martial arts, and so on. The preferences regarding the "HOW" and "WHAT" are highly subjective, and are based on personal abilities, interests, preferences, and available options. The "WHERE" dimension is also important, as different location options may also affect PA engagement. Examples include home-based activities, club-based activities, outdoor activities, and community-based activities. The "WHERE" location involves first the availability of PA in different locations and second the preferences of potential participants considering these activities. While selecting among the different available options depends usually on participant-related characteristics, the existence of the different options is usually affected by technical resources and space allocation. In this regard, and in line with our study objectives and research questions, the built environment characteristics, may also affect the design of dedicated measures promoting PA. Active travel increases PA, and is particularly appealing to employed young women, who do not own or have access to a private car, as car ownership can reduce utilitarian walking and cycling, regardless of gender, hence affecting moderate PA levels (Dyck et al., 2010).

## 4.1 Effects of the built environment on physical activity

One of the objective built environment variables affecting MPA levels of women in the Balkan countries was found to be street-length density, which is marginally significant and positively correlated with MPA, indicating that areas with densely connected networks promote more MPA. This finding aligns with previous research, which has shown that community design with higher street connectivity promotes walking and cycling and encourages active travel by offering more direct and safer routes (Saelens and Handy, 2008; Frank et al., 2005). Similarly, Sallis et al. (2012) demonstrated that urban areas with high intersection density and accessible infrastructure encourage greater PA participation. However, the relationship between street connectivity and MPA in our study appears inconsistent, as some countries with higher street connectivity (e.g., Greece) report lower MPA and VPA levels and vice-versa (e.g., Serbia). This suggests that not only street connectivity, but additional factors also affect the PA levels (e.g., weather conditions, pedestrian areas, sidewalks, lighting, overall safety etc.). For example, in our study, in Athens, pedestrian infrastructure is identified as low quality with narrow or non-existent sidewalks and bad surface conditions, making the streets unattractive for walking, running, and cycling. Sallis et al. (2012) reported that the availability of high-quality infrastructure for walking and cycling (e.g., sidewalks, bike paths, crosswalks) promotes active travel PA among the population, hence the lack of such infrastructure discourages PA. Additionally, high temperatures during summer months can be an additional burden and further discourage PA. A similar situation is observed in Bucharest, where, despite the relatively good infrastructure and street connectivity, and the increased investments in cycling infrastructure and pedestrian zones (including over 25 kilometers of dedicated cycling lanes), participants from Romania exhibited the lowest reported minutes for MPA and the second lowest for VPA. On the contrary, Niš (Serbia) is reported to have the second lowest values for street connectivity, but still exhibits the highest reported minutes for VPA, and a higher level of MPA compared to Greece and Romania. Although the dedicated infrastructure for walking and cycling is not recognized as a priority for the city of Niš, it is described as a relatively pedestrian-friendly city, that offers a network of sidewalks and pedestrianized areas, especially in its central part. Cycling also gained popularity among residents, as a result of the design of dedicated cycling lanes and the adoption of a bike-sharing scheme. These examples suggest that additional objective factors (infrastructure, climate, air pollution etc.), as well as habits, cultural, and social factors also play a role when considering PA behaviors (Sallis et al., 2012). Societal barriers are especially present in Balkan countries. Pojani et al. (2017), based on results from a study conducted in the Netherlands, Albania and Kosovo, reported that Balkan cities face societal barriers such as the high status associated with car ownership and the perceived incompatibility between cycling and the female gender. This discourages people from cycling, particularly limiting PA engagement resulting from utilitarian walking or cycling trips. The location of places for walking and cycling is also important. Zhang et al. (2019) identified significant positive associations between park-based leisure PA, park lighting, and walking and cycling trails. Among the contributing subjective built environment variables, the availability of shops in the neighborhood was found to be significantly associated with an 8% decrease in MPA. Although proximity to shops encourages walking, which is a light-intensity physical activity, participants may not include shopping time when reporting MPA. Previous studies have noted similar trends, where accessibility to retail destinations is linked to increased walking, but not necessarily with higher-intensity physical activities (Giles-Corti et al., 2005).

On the other hand, the presence of cycling routes near the living area is positively correlated with MPA, supporting the notion that dedicated cycling infrastructure promotes active travel and physical activity (Winters et al., 2010; Pojani et al., 2017). Living close to a natural outdoor environment suitable for different forms of PA was found positively correlated with the PA levels of adults in a study performed in different European cities (Triguero-Mas et al., 2017). The observed 8% increase in MPA due to the presence of cycling routes is consistent with prior findings, highlighting the importance of cycling infrastructure in active commuting (Buehler and Pucher, 2012; Pojani et al., 2017).

Two objective built environment variables, link density and link-node ratio, were found to significantly affect vigorous physical activity. The positive relationship between link density and VPA suggests that areas with a higher number of intersections per unit area facilitate more vigorous activity, likely by promoting walkability and access to various destinations (Ewing and Cervero, 2010). However, the positive association between the link-node ratio and VPA suggests that as the number of streets divided by intersections increases, connectivity weakens, potentially reducing accessibility and engagement in vigorous activity. This finding is somewhat counterintuitive and warrants further investigation.

Similarly to the MPA model, the subjective built environment variables function in the same manner. The availability of shops is negatively correlated with VPA, reinforcing the idea that shopping-related movement is generally of lower intensity. The availability of cycling routes shows a significant positive relationship with VPA, with an 11% increase in vigorous PA, further confirming the role of cycling infrastructure in promoting active travel (Buehler and Pucher, 2012).

Overall, these findings highlight the importance of both objective and subjective built environment factors in shaping physical activity behaviors. Higher street connectivity and cycling infrastructure appear to facilitate moderate and vigorous physical activity, whereas proximity to shops may promote lighter activity such as walking rather than MPA or VPA. These results suggest that urban planning and transportation policies should prioritize the development of connected street networks, with available sidewalks, safe pedestrian areas, and dedicated cycling infrastructure to encourage higher levels of physical activity among young women. In this regard, it should not be forgotten to consider issues that arise from unplanned urban expansions leading to environmental and health hazards, including air pollution, diminished safe spaces for walking and cycling, and so on (Agarwal et al., 2007).

Positive practices, such as bike-sharing schemes, community support in creating green spaces and urban zones that encourage PA, subsidies for bicycles and other micro-mobility transport modes purchase, and other activities like forming walking and cycling groups can serve as effective strategies. In this regard, in PA Factsheets from 2021, WHO included urban planning in one of the policy responses aimed at improving PA levels among EU member countries. Within these recommendations, it is suggested that "all population groups should have access to infrastructure conducive to active leisure time." Guidelines have been prepared within the European Commission-funded project Improving Infrastructures for Leisure-time Physical Activity in the Local Arena (IMPALA), including sports facilities, infrastructure, and urban "green" and "blue" spaces" (WHO, 2021 PA factsheet, pp. 11). This has initiated the design and implementation of specific actions and policies in the EU countries. For example, in Greece a national bicycle strategy and a national accessibility plan have been designed. Within this framework, a "bicycle observatory" was developed to monitor the implementation of the strategy, assess cycling infrastructure and record the number of daily bicycle trips (WHO, 2021, pp. 108).

## 4.2 Effects of the built environment on mental well-being

The relationship between built environment variables and the mental well-being of young women in the participating countries comprised the second research question of the present study. The respective MLR model for mental well-being highlights significant associations between subjective built environment variables and perceived well-being. Notably, no objective built environment variable related to the street network was found to be significant. Instead, five subjective built environment variables contribute significantly to perceived well-being, explaining 7.8% of the variance. They are the availability of cycling routes, the extent of land use diversity, the attractiveness of cycling routes, the overall attractiveness of the neighborhood and the presence of green areas and trees.

The availability and attractiveness of cycling routes in the neighborhood were identified as relevant and important for mental well-being. These factors were also found to be associated with PA, highlighting the link between well-being and PA. This finding is in line with previous studies noting that access to active transport infrastructure enhances physical activity levels (Mueller et al., 2015) and mental health by reducing stress and promoting outdoor engagement (Ma and Dill, 2015). To comprehend outdoor engagement and its impact on well-being, it is worth emphasizing the links between outdoor activities and spending time outdoors with well-being. Engagement in outdoor activities encourages positive emotions and enthusiasm providing pleasure, enjoyment, and personal satisfaction, comfort and intense emotions, satisfaction from personal achievements, vital strength and experience from nature (Clough et al., 2016; Tsaur et al., 2015; Crust et al., 2013). Spending time outdoors enhances awareness of personal health and its importance for overall well-being. It fosters a commitment to develop healthy habits and cultivates a healthy and active lifestyle as a personal goal, offering numerous benefits for both mental and physical well-being (Deenihan and Caulfield, 2014). Evidence on the positive correlations of outdoor activities on different dimensions of health and well-being can be found in several studies. Examples include revitalization, and reduction in tension, confusion, anger, and depression (Eigenschenk et al., 2019), greater enjoyment (Crust et al., 2013), improvement of individual well-being and increased perception of personal health and stronger nature-relatedness (Puhakka et al., 2018). This is also confirmed by the results of the present study, which showed that the presence of green areas and trees is associated with a 6% increase in mental well-being. This finding supports the growing body of evidence indicating that exposure to green spaces and tree-lined streets enhances psychological well-being by reducing stress and promoting relaxation (Gascon et al., 2015), and by increasing enjoyment (Crust et al., 2013).

The attractiveness of cycling routes and the overall attractiveness of the neighborhood for walking and cycling were also found to be positively associated with well-being, as they increased the well-being scores by 7 and 10%, respectively. These results reinforce the notion that aesthetically pleasing and accessible pedestrian and cycling environments contribute to mental health benefits (Mitchell et al., 2015), emphasizing the links between aesthetics and well-being.

The presence of diverse land uses in the neighborhood comprises yet another significant predictor associated with an 8.5% increase in well-being. Land use diversity facilitates access to commercial, recreational, and institutional establishments that are located within close proximity, thereby increasing the likelihood of utilitarian active travel, and hence PA levels and well-being. As indicated in our study, the different cities offer a variety of available facilities and spaces that meet PA needs and support mental well-being. This aligns with research emphasizing the psychological benefits of mixed land use, which provides greater opportunities for social interaction, active travel, and access to essential services (Sugiyama et al., 2008). Areas with a diverse mix of land uses encourage walking and cycling by providing essential services close to residential areas (Frank et al., 2005), affecting positively PA levels as people are more likely to walk or bike to nearby destinations (Saelens and Handy, 2008). It also supports community engagement and improves mental well-being by offering various public spaces and social opportunities (Sugiyama et al., 2008).

Overall, these findings highlight the importance of land use planning and urban design in shaping physical activity behaviors and mental well-being. Well-connected street networks and dedicated cycling infrastructure appear to facilitate both moderate and vigorous physical activity. Additionally, aesthetically pleasing and diverse land uses, including green spaces and pedestrian-friendly environments, contribute to improved mental well-being. These results underscore the need for policymakers and urban planners to prioritize active transport networks and mixed land-use designs to support both physical and mental health outcomes among young women.

By assessing the differences in the effects and coefficients of subjective and objective built environment features on levels of physical activity and mental well-being, the results showed that perceived environment variables had stronger associations than objective ones. This finding suggests that mobility behavior and well-being among young women in Balkan countries may be more closely linked to their perceptions of urban design, such as perceived neighborhood safety, mixed land use, attractiveness, and aesthetic quality than to the actual physical characteristics of the environment.

It is also important to note that the objective built environment features used in this study primarily reflected street-network characteristics, rather than detailed measures of land use or urban design elements. Therefore, to better understand the differences between subjective and objective impacts of the built environment, it is necessary to conduct direct, one-to-one comparisons between corresponding variables in future research.

## 4.3 Limitations of the study

This study presents interesting findings on the effects of built environment on the PA levels and mental well-being of young women from Balkan countries. However, it has specific limitations that may reduce its representativeness and generability potential.

The structure of the utilized sample is identified as one of the study limitations. This study was conducted in five different cities, with a sample that is diverse in terms of socio-economic structure, comprising mainly students in Romania and North Macedonia, employed women in Serbia, and mixed groups in Greece and Bulgaria. Therefore, the generalization of the findings should be made with care.

Using self-reported tools for physical activity and mental well-being, as well as subjective reports of some variables of the built environment, can be another limitation. Supplementing self-reported tools with objective measures (e.g., accelerometers, GPS tracking, or psychological assessments) could enhance data accuracy.

The cross-sectional design is another identified limitation. The study is based on a cross-sectional dataset, meaning it captures a single point in time. As a result, causality cannot be established between land use diversity, physical activity and mental well-being. Longitudinal or experimental studies would provide stronger causal inferences. Longitudinal data can provide a more accurate and comprehensive understanding of how built environment features influence PA and well-being in Balkan countries. So, the current study suggests that future studies should examine the correlates and determinants of physical activity and mental well-being using longitudinal designs. Such an approach would allow researchers to better capture causal relationships over time and account for seasonal, social, or environmental changes that may influence behavior and health outcomes.

While control variables were included, other factors; such as personal motivation, weather conditions, safety concerns, air pollution, and cultural norms may also influence PA levels and well-being, particularly among women. These factors were not directly accounted for in the model, presenting an additional limitation. Although the aim of this paper was to examine the relationship between subjective and objective built environment features and physical activity and well-being, it is important to acknowledge that contextual factors and cultural variation can significantly shape perceptions of the built environment. This paper suggests that incorporating some of these variables in future studies would provide a deeper and more comprehensive understanding of the research problem.

# 5 Conclusion

This study highlights the critical role of both objective and subjective built environment factors in shaping physical activity behaviors and mental well-being among young women in the Balkans. Findings indicate that higher street connectivity and cycling infrastructure promote moderate and vigorous physical activity, while proximity to shops may encourage lighter activities such as walking. Additionally, aesthetically pleasing and diverse land use, including green spaces and pedestrian-friendly environments, is associated with enhanced well-being.

From a policy perspective, urban planning and transport strategies should prioritize the development of connected street networks, safe pedestrian areas, and dedicated cycling infrastructure to encourage active lifestyles. Best practices, such as bike-sharing programs, subsidies for active transportation, and community initiatives supporting physical activity, can further increase PA engagement. Policymakers and urban planners should integrate these findings into future development strategies to create healthier and more livable cities for young women and the broader population.

# Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

# Ethics statement

Ethical approval was not required for the studies involving humans because this study does not have intervention on Human. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

# Author contributions

HM: Conceptualization, Writing – review & editing, Funding acquisition, Software, Writing – original draft, Project administration, Methodology, Supervision, Visualization. MeM: Writing – original draft, Writing – review & editing, Conceptualization, Project administration, Validation, Methodology, Data curation. GL: Writing – original draft, Supervision, Investigation, Validation, Writing – review & editing. IS: Writing – original draft, Investigation, Supervision, Writing – review & editing. BP: Writing – review & editing, Writing – original draft, Investigation. SM: Writing – original draft, Writing – review & editing. MD: Writing – review & editing, Writing – original draft. MaM: Writing – original draft, Writing – review & editing.

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## Conflict of interest

The 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.

## Generative AI statement

The authors declare that no Gen AI was used in the creation of this manuscript.

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# Gender-based equality in sport and women's presence in sport and sports leadership structures matrix 1.0 nation reports: a protocol for national and global annual report

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This protocol was developed to facilitate the collection of up-to-date data and produce a comprehensive annual assessment of gender-based equality in sport and the representation of women in sports and leadership roles. Its goal is to provide evaluators with a standardized methodology for identifying and assessing key indicators related to gender equality and women's participation in sport at national, regional, and global levels. By focusing on a range of indicators, this protocol aims to highlight the current state of gender representation in sport and identify specific barriers to achieving equality. The protocol includes 19 sociodemographic indicators, accessible online, to characterize the demographic profile of participating countries. Additionally, it proposes 20 content indicators specifically focused on assessing women's presence in sport and leadership roles, as well as policies promoting gender equality. Each content indicator will be evaluated through separate analyses using a ten-point grading scale, allowing for a nuanced understanding of challenges and progress in this area. To ensure a dynamic connection between research and practice, the protocol encourages national evaluators to meet annually, producing national reports known as National Reports. These reports will offer detailed and ongoing assessments of gender equality in sport, with outcomes designed to inform policy development and advance gender equity in sports and leadership structures.

KEYWORDS
gender equality, women's leadership, country factsheets, monitoring, female, surveillance

## 1 Introduction

Gender refers to the roles, behaviors, activities, and attributes that a society associates with masculinity and femininity (1). Gender equality, as defined by the United Nations, is the state in which women and men have equal rights and opportunities across all sectors of society. It is a condition where the diverse behaviors, aspirations, and needs of both women and men are equally valued (2).

Achieving gender equality involves attaining equal representation across various measurable outcomes, such as equal access and participation, equal representation in leadership, equal pay and rewards, and equal media coverage and visibility (3). Significant progress has been made in gender equality in sports globally. For example, at the Tokyo 2020 Olympics, women made up 48.8% of participants (4), bringing the event close to achieving gender parity. Additionally, the presence of women in leadership roles within international sports federations has increased, with women now holding about 21% of leadership positions (5). Despite this progress, challenges remain. Achieving full gender equality is an ongoing struggle, and maintaining these gains requires continuous effort and commitment.

Gender inequality brings a number of interconnected disadvantages. Women and girls often have limited access to education, which affects their opportunities in later life. This limits their potential, depriving companies and economies of valuable skills and talents. As a result, gender inequality contributes to economic inefficiency. Moreover, male-dominated power structures lead to social injustice, which can result in health consequences, violence, political exclusion, and social instability. Given these challenges, gender equality is a core value of the European Union (EU), embedded in its legal frameworks, policies, and strategies (6). The EU has long been committed to promoting gender equality in sports and closing gender gaps. Through programs such as Erasmus + Sport, the EU supports projects and partnerships that aim to reduce gender inequality in sports by fostering women's leadership, participation, and inclusion in various sectors. One such initiative, the SWOST project, inspired the authors of this study to develop a gender equality monitoring system. This system aims to provide updated data on gender equality in sports, motivating ongoing progress and keeping the goal of gender equality at the forefront.

While literature emphasizes the need for an organized monitoring system, no universally accepted framework currently exists, and many countries do not implement such systems. Several institutions monitor gender equality to identify gaps and inequalities, providing a foundation for shaping policies that promote gender equality. However, monitoring efforts are often underdeveloped or limited, and their effectiveness varies depending on political will, available resources, and the quality of data collected. The European Union's Gender Equality Index (7) provides valuable data, but it is not sufficiently detailed for local-level application. A comprehensive and consistent monitoring system is essential, followed by concrete actions aimed at reducing gender inequality.

The goal of this study is to develop a methodology that will provide a reliable foundation for tracking specific indicators over time, allowing for the assessment of changes in gender equality at national, regional, and global levels. This will involve collecting relevant data on gender-based equality in sports, women's participation in sport, and women's presence in sports leadership roles, along with the barriers to achieving these outcomes in each country. Periodic evaluations will inform the creation of National Reports, which will then be consolidated into a global report. National Reports will provide actionable insights to inform sports policies and promote structural gender equity in leadership and participation.

## 2 Materials and methods

A team of content experts has been assembled to develop a new study protocol designed to serve as a reliable tool for collecting up-to-date data on gender-based equality in sport and the presence of women in sports and leadership structures. This protocol, built around a set of specific indicators to which grades will be assigned, is supported by the SWOST (Sport Without Stereotypes) project team under the Erasmus + Sport program (Project No: 622774-EPP-1-2020-1-IT-SPO-SCP).

The study protocol will encourage national evaluators (researchers) to meet annually, review the most relevant evidence related to gender equality in sport and women's representation in sports leadership, and produce national reports (National Reports). These reports will ensure dynamic and effective connections between research and practice. The National Reports will be crucial in guiding discussions that promote actions aimed at enhancing gender equality and increasing women's representation in both sport and leadership positions, contributing to more inclusive and equitable environments within the sports industry.

The protocol draws on the authors' extensive experience with leading methodologies for assessing gender equality globally (8–10). Its purpose is to support individuals and organizations dedicated to promoting gender equality in sport and women's leadership in sport. The primary outcome of this study protocol will be the National Reports, created through a consistent, transparent process of gathering and compiling the best available evidence. These factsheets, available in both concise and detailed formats in English, will be shared through media and public awareness campaigns, knowledge exchanges at scientific conferences and workshops, and collaborations with relevant stakeholders.

This protocol includes 19 sociodemographic indicators that are publicly available online and will be used to assess the characteristics and demographic profiles of the participating countries. These indicators are: country; total population; urban population; female population percentage; human capital index; GDP per capita; GDP growth; unemployment rate; literacy rate (overall and by gender); educational attainment (percentage with tertiary education overall and by gender); labor force participation (overall and by gender); government spending on education; government spending on sports and recreation; internet usage; life expectancy; physical activity prevalence; workforce gender distribution; age distribution (youth and adult populations); and socioeconomic status (poverty rate or income inequality index) (Table 1).

TABLE 1 Country's demographic profile.

| Questions (unit) | Definition | Reason for inclusion | Application in protocol |
|---|---|---|---|
| Country (–) | Name of the country for which data are provided | Identifies the research entity | Specifies the national context of evaluation |
| Total population (number of people) | Total number of inhabitants | Basis for ratios and weightings | Used to normalize indicators |
| Urban population (%) | % of population living in urban areas | Reflects differences in infrastructure availability | Adjusts protocol for urban vs. rural settings |
| Female population percentage (%) | % of population that are women | Key for assessing gender dynamics | Ensures gender-specific analysis |
| Human capital index (number between 0 and 1) | Value between 0 and 1 reflecting education, health, and skills | Measures development level and human resource potential | Provides broader socio-economic context |
| GDP per capita (current US$) | GDP in current USD per person | Indicator of economic development | Informs financial capacity for protocol implementation |
| GDP growth (annual %) | Annual GDP growth rate | Measures economic trend | Provides temporal context for evaluation |
| Unemployment rate, total (% of total labor force) | % of working-age population without employment | Affects socio-economic status and time for activities | Weights access to sports facilities |
| Literacy rate, adult total and by gender (% of people ages 15 and above) | % of adults aged 15+ who can read and write (overall and by gender) | Crucial for understanding materials and communication | Tailors complexity of information |
| Educational attainment, percentage with tertiary education overall and by gender (%) | % of population with tertiary education (overall and by gender) | Indicator of educational structure and gender gaps | Used to plan educational and promotional measures |
| Labor force participation, overall and by gender (% of people ages 18 and above) | % of population aged 18+ in the workforce (overall and by gender) | Shows economic engagement and gender disparities | Informs resource availability for evaluators |
| Government expenditure on education, total (% of government expenditure) | % of total government expenditure on education | Indicator of educational policy priority | Contextualizes investment in human capital |
| Government expenditure on sporting and recreational services, total (% of government expenditure) | % of total government expenditure on sports and recreation | Reflects support for sports programs | Assesses resources available for sports infrastructure |
| Individuals using the Internet (% of population) | % of population using the internet | Determines feasibility of digital engagement and data collection | Guides online components of the protocol |
| Life expectancy at birth, total (years) | Average number of years a newborn is expected to live | Proxy for health and living standards | Benchmark for health-related protocol targets |
| Physical activity prevalence (%) | % of adults not meeting physical activity guidelines | Shows baseline activity level | Helps set targets for increasing activity |
| Workforce gender distribution (%) | % of males and females in the workforce | Reflects gender structure of the labor market | Ensures gender-balanced analyses |
| Age distribution, youth and adult populations (%) | % of population by age groups (youth and adults) | Measures demographic structure | Adjusts protocol for different age groups |
| Socioeconomic status, poverty rate or income inequality index (% or number between 0 and 1) | Poverty rate or Gini index of income inequality (as % or 0–1 index) | Reflects economic inequalities | Targets interventions in socially excluded groups |

The protocol also identifies 20 content indicators focused specifically on women's participation in sport and sports leadership, as well as policies for advancing gender equality. These include: Women's participation in competitions; Women's presence in the Olympic team; Women's presence in Ministry responsible for sport staff; Women's presence in National Olympic Committee leadership; Women's presence in National Paralympic Committee leadership; Women's presence in national sport federations management structures; Woman as a president of a national sport federation; Women as board members in a national sport federation; Women as assembly members in national sport federations; Women in coaching roles; Women in elite coaching roles; Women in sports referee roles; Women as delegates; Women's presence in medical staff personnel; Women's presence in sports media staff; Written policy or legislation on gender equality; Statutes revised and adapted from a gender perspective; Availability of leadership training for women; Clear gender-friendly recruitment procedures; Policy for combating gender-based violence (Table 2).

The authors of the protocol plan to regularly gather input from stakeholders to enhance and update the list of indicators annually.

The 20 content indicators were selected based on: (1) relevance to gender equality monitoring in sport, (2) precedence in international frameworks (e.g., EU Gender Equality Index) (7), (3) findings from the State of PLAY National Framework Analysis—one of the key outputs of the SWOST project (11) and (4) feasibility of data collection across countries. The process was further informed by the authors' own methodological expertise—acquired through previous development of gender-equality assessment tools and the other experience gained on the SWOST project—and by consultations with academic experts in sport science, gender studies, and policy analysis, thereby ensuring the indicators' applicability, validity, and operational feasibility.

Additionally, they will conduct external evaluations to assess the protocol's inputs, outputs, and both immediate and long-term outcomes.

To assess each of the content indicators, a separate analysis will be conducted using a six-point grading scale (5 = excellent; 4 = very good; 3 = good; 2 = fair; 1 = poor; 0 = lacking reliable information). The grades will be determined based on data from scientific articles published within the last 10 years, as well as secondary sources such as government and nongovernment reports and relevant online content from the specified period. To reduce bias and ensure consistency, sources will be assessed according to a reliability hierarchy: (1) peer-reviewed scientific publications, (2)

TABLE 2 GBES-WPSLS Matrix 1.0 Indicators and Benchmarks Used to Guide the Grade Assignment Process.

| Indicator | Benchmark |
|---|---|
| Women's Participation in Competitions | % of women participating in national and international sports competitions, including elite, amateur, and youth levels. |
| Women's Presence in the Olympic Team | % of women represented in national Olympic teams across various sports. |
| Women's Presence in Ministry Responsible for Sport Staff | % of women in staff roles within government ministries or departments responsible for sports and recreation. |
| Women's Presence in National Olympic Committee Leadership | % of women in leadership roles (e.g., president, vice-president, executive director) within National Olympic Committees (NOCs). |
| Women's Presence in National Paralympic Committee Leadership | % of women in leadership roles within National Paralympic Committees (NPCs). |
| Women's Presence in National Sport Federations Management Structures | % of women in senior management or executive roles within national sport federations (e.g., directors, managers). |
| Women as President of a National Sport Federation | % of women serving as presidents of national sport federations. |
| Women as Board Members in a National Sport Federation | % of women serving as board members within national sport federations. |
| Women as Assembly Members in National Sport Federations | % of women serving as assembly or governing body members in national sport federations. |
| Women in Coaching Roles | % of women in coaching roles at various levels of sport, from grassroots to elite. |
| Women in Elite Coaching Roles | % of women in coaching roles at the elite or professional level, including national and international team coaches. |
| Women in Sports Referee Roles | % of women in officiating roles in sports, including referees, umpires, and match officials at all levels of competition. |
| Women as Delegates | % of women serving as official delegates or representatives at national or international sports events, conferences, or governing bodies. |
| Women's Presence in Medical Staff Personnel | % of women in medical roles (e.g., physicians, physiotherapists, nutritionists) within sports teams or federations. |
| Women's Presence in Sports Media Staff | % of women in sports media roles, including journalists, reporters, analysts, and broadcasters. |
| Written Policy or Legislation on Gender Equality | % of national sports organizations that have formal written policies or legislation addressing gender equality in sport, including participation and leadership. |
| Statutes Revised and Adapted from a Gender Perspective | % of national sports federations or committees that have revised their statutes or regulations with a gender perspective in mind, ensuring equal opportunity for women. |
| Availability of Leadership Training for Women | % of national or international sport organizations offering specific leadership training or development programs for women in sport. |
| Clear Gender-Friendly Recruitment Procedures | % of sport organizations with formal, clear, and gender-friendly recruitment procedures to ensure equal opportunity for women in sport roles. |
| Policy for Combating Gender-Based Violence | % of national sport federations or organizations with active, clear policies or programs aimed at combating gender-based violence in sports environments. |

official government and intergovernmental documents, (3) reports by recognized non-governmental organizations, and (4) online media or web content, which will be cross-verified where possible. Evaluators are instructed to prioritize higher-tier sources and to document the rationale for using lower-tier materials when necessary. The findings will then be synthesized, and the grading process will be finalized using the framework outlined in Table 3. Each indicator will be thoroughly discussed until a consensus on the grade is reached among the evaluators. While evaluators are expected to reach consensus on the grade for each indicator, a structured conflict resolution procedure is in place. In cases of disagreement, a two-step resolution process will be used: (1) evaluators will revisit the evidence and justify their grading using a standardized justification form; (2) if disagreement persists, a third independent evaluator will be invited to provide an assessment, and the final grade will be determined by majority decision.

The present protocol adopts a binary operationalization of gender (women and men), which aligns with the structure of most current sports governance systems and available data sources. While the authors acknowledge the importance and existence of transgender and gender non-conforming individuals in sport, the scope of this study is limited to cisgender categories due to the availability, comparability, and consistency of existing datasets. This does not imply exclusion, but rather reflects a pragmatic decision for standardization in cross-country comparisons. Future iterations of the protocol may expand to incorporate more inclusive gender categories as data collection practices evolve.

TABLE 3 GBES-WPSLS Matrix 1.0 Grading System.

| Grade | CI | Description |
|---|---|---|
| 5 | 40.1%–50% | Excellent |
| 4 | 30.1%–40% | Very good |
| 3 | 20.1%–30% | Good |
| 2 | 10.1%–20% | Fairly good |
| 1 | 0.1%–10% | Poor |
| 0 | 0 | Without reliable information |

CI, class intervals represent the range or difference between the upper and lower class limits of a given data set.

The grading thresholds applied in this protocol—such as the definition of "excellent" performance corresponding to at least 40.1% representation—are grounded in the theoretical framework proposed by Kanter (12), who emphasized that true equality between groups is achieved when each gender attains a minimum threshold of 40% participation. This principle has also been adopted in institutional practice. For instance, the European Commission (13) set explicit targets requiring a minimum of 40% representation of both women and men on the boards of national sports organizations, expert working groups in sport, and among athletes and coaches. These thresholds provide a

TABLE 4 Full search syntax used for each database.

| Database | Search syntax |
|---|---|
| Scopus | title-abs-key("gender equality" OR "women in sport" OR "female in sport" OR "women leadership" OR "female leadership" OR "women athletes" OR "female athletes" OR "gender equity" OR "sports leadership") AND title-abs-key([country]) |
| Web of Science, SportDiscus (through EBSCOhost) | ("gender equality" OR "women in sport" OR "female in sport" OR "women leadership" OR "female leadership" OR "gender equity") AND ("women athletes" OR "female athletes" OR "sports leadership") AND [country] |
| Open Access Theses and Dissertations (OATD), Networked Digital Library of Theses and Dissertations (NDLTD) | ("gender equality" OR "women in sport" OR "female in sport" OR "women leadership" OR "female leadership" OR "gender equity") AND ("women athletes" OR "female athletes" OR "sports leadership") AND [country] |
| Google | "gender equality" OR "women in sport" OR "female in sport" OR "women leadership" OR "female leadership" OR "sports leadership" AND "women athletes" OR "female athletes" AND [country] |

You can replace [country] with the name of a specific country or region depending on your research focus.

normative benchmark for evaluating structural gender balance and inform the cut-off points used in our grading scale.

The reliability of content analysis in this study on Gender-Based Equality in Sport and Women's Presence in Sport and Sports Leadership Structures will involve the operationalization of key concepts related to gender equality, women's participation, and leadership roles in sport. This includes training coders to accurately implement these concepts, as well as assessing coder reliability throughout the evaluation process (14). To address potential biases, the inter-rater reliability will be calculated using Cohen's kappa coefficient (κ), as recommended by McHugh (15). Research articles will be sourced from electronic databases such as SportDiscus, Scopus, PubMed/MEDLINE, and Web of Science. Additional resources like Open Access Theses and Dissertations (OATD), the Networked Digital Library of Theses and Dissertations (NDLTD), and Google will be used to find theses, dissertations, and other relevant documents or online content to assess the indicators. The full search syntax for each database will be detailed in Table 4.

The overall evaluation process is summarized in the flowchart below (Figure 1), which outlines the main steps for national teams from data identification to final reporting.

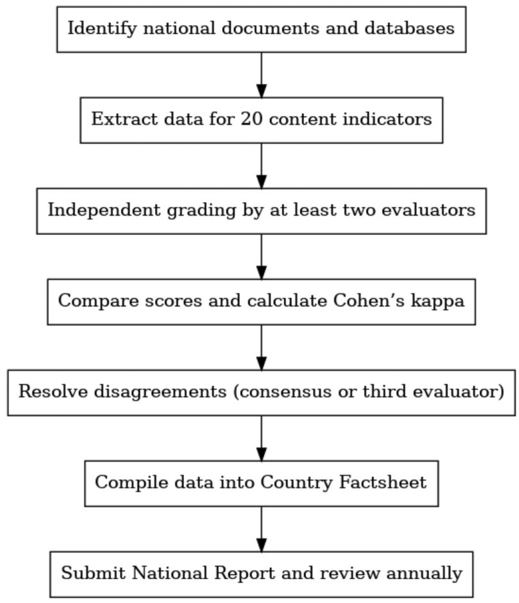


FIGURE 1
Step-by-step protocol for national-level data collection, indicator grading, consensus building, and reporting within the Gender-Based Equality in Sport Matrix 1.0 framework.

# 3 Expected results

This protocol is designed to enable evaluators to gather current data and produce a comprehensive annual assessment through specific indicators, ensuring that the results reflect the most relevant evidence related to gender equality in sport and the presence of women in sports leadership roles across countries. It will also identify specific barriers women face in participating in sports or assuming leadership positions.

Evaluators will assess the results by comparing their grades, followed by calculating the initial inter-judge agreement using Cohen's kappa coefficient (κ). After reviewing all available data, evaluators will seek additional information to maximize inter-judge agreement, aiming for a kappa value of 1, indicating perfect agreement. A high level of intercoder reliability will confirm that all coders are thoroughly familiar with the coding protocol and codebook.

The expected results will be presented as scores (0–5) for each content indicator, awarded based on the quality and quantity of selected documents (scientific articles, governmental and nongovernmental reports, and online content). For each Country Factsheet, 20 content indicators will be reviewed to assess the status of gender equality in sport and women's presence in sports leadership. A total average score for these 20 indicators will be calculated, providing a snapshot of the status of gender equality and women's leadership in sports within each country.

Additionally, this section will outline the primary target audiences and the expected outcomes of the study protocol. The main audiences for the National Reports are sports organizations, policymakers, and educators whose work influences gender equality and the inclusion of women in sports and leadership roles. Media outlets are also considered key stakeholders, as their role in raising public awareness and promoting gender equality in sports is vital. While the general public may be indirectly impacted through media coverage, the protocol's core goal remains to inform practitioners, policymakers, and educators.

The dissemination of the National Reports will grow through social media campaigns and annual releases, focusing on recommendations to improve gender equality in sport and enhance the presence of women in leadership roles within sports organizations.

Immediate outcomes will include increased awareness among decision-makers about the importance of gender equality in sport, the contribution of the National Reports to raising awareness, and media engagement to highlight the importance of women's representation in sports. This will also involve the continuous engagement of relevant organizations advocating for policy and program changes to enhance opportunities for women in sports. Furthermore, the National Reports will be recognized as a reliable source of data regarding gender equality in sports and an advocate for women athletes and leaders.

Intermediate outcomes will focus on creating policies, programs, and campaigns by government and non-government stakeholders aimed at increasing opportunities for women in sports leadership and participation. Long-term outcomes will be measured by the percentage of women participating in competitive sports and holding leadership roles, reflecting the success of policies and programs promoting gender equality and women's representation in sports leadership.

## 4 Limitations

While this protocol offers a structured framework for detecting and quantifying equality across socio-demographic groups, it is not without limitations. First, the focus on equality—operationalized through proportional representation—does not guarantee equity, which requires tailoring resources and access to group-specific needs rather than distributing them identically. Consequently, participants who appear equally represented may still face unequal opportunities due to socio-economic status, educational background, or cultural barriers (16). Second, the current binary gender categorization (male–female) overlooks the complex, intersectional dimensions of identity described by Crenshaw (17), including race, class, sexual orientation, and other axes of marginalization. By not accounting for these overlapping inequalities, the protocol cannot fully capture or address compounded disadvantage. We regard these shortcomings as areas for future enhancement, envisioning subsequent iterations that introduce weighted adjustments for socio-economic factors and expand gender classification to an intersectional model in line with contemporary scholarship. In the next phase, we will pilot test socia-economic weighting adjustments to evaluate their feasibility before extending to a full intersectional framework.

## Ethics statement

Ethical approval was not required for the study involving humans in accordance with the local legislation and institutional requirements.

## Author contributions

BaK: Writing – original draft. BoK: Writing – review & editing. KG: Writing – review & editing. VG: Writing – review & editing. AIB: Writing – original draft. MM: Writing – original draft. BM: Writing – original draft.


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## Conflict of interest

The 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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