International Journal of
Mental Health Promotion

Tech Science Press

http://doi.org/10.32604/ijmhp.2026.078865

ARTICLE

Acute Aerobic Exercise Is Associated with Better Cognitive Reappraisal in Healthy Postmenopausal Women: Evidence from fNIRS

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Received: 09 January 2026; Accepted: 30 March 2026; Published: 30 July 2026

ABSTRACT: Objectives: Postmenopausal women experience hormonal and psychosocial changes that can affect emotion regulation. Although exercise may enhance cognitive control during emotion regulation, evidence on prefrontal activation in this population is limited. This study examined whether acute moderate-intensity aerobic exercise influences emotion regulation and prefrontal activation in postmenopausal women. **Methods:** Postmenopausal women (≥12 months since last menstruation) were randomised to a moderate-intensity aerobic exercise condition or a time-matched sedentary control condition (n = 102). Analyses included participants with usable behavioural and fNIRS data (exercise n = 32; control n = 35). The exercise group completed 30 min of cycling at 50–75% age-predicted HRmax (RPE 12–14), and the control group completed 30 min of seated rest. fNIRS measured task-evoked oxygenated haemoglobin changes in prefrontal subregions before and after the intervention. **Results:** Negative images were rated as more aversive than neutral images ($F(3, 195) = 13.73$, $p < 0.001$), confirming task validity. A 2 × 2 × 4 mixed ANOVA showed significant main effects of group, time, and emotion regulation strategy, and a significant Group × Emotion Regulation interaction ($F(3, 195) = 7.18$, $p < 0.001$). Compared with controls, the exercise group reported lower negative affect during reappraisal and suppression (all $p < 0.001$). NIRS showed significant Group × Time interactions in the left VLPFC, right VLPFC, and left DLPFC during reappraisal (all $p < 0.05$). **Conclusions:** Acute aerobic exercise reduced negative emotions and improved emotion regulation.

KEYWORDS: Acute aerobic exercise; postmenopausal women; emotion regulation; functional near-infrared spectroscopy

1 Introduction

Mood disturbances are particularly common in postmenopausal women and are most often expressed as depression, anxiety, and stress reactivity [1,2]. Compared with younger women, they face higher risk due to hormonal decline and midlife psychosocial stressors [3,4]. Such problems reduce quality of life, increase vulnerability to long-term health problems, and are often accompanied by impairments in executive function (EF) and emotion regulation [5,6]. Epidemiological studies report the prevalence of depression as high as approximately 28.0% globally [2,7]. Importantly, postmenopausal women also represent a theoretically relevant group for studying exercise-related changes in emotion regulation, because hormonal decline has been linked to alterations in prefrontal functioning and cognitive control processes that support adaptive regulation. The high prevalence and large population size highlights the urgent need for intervention strategies. Acute aerobic exercise (AAE) has emerged as a promising behavioural intervention [5].

AAE is defined as a single bout of aerobic activity, characterised by a duration of 10 to 60 min that can produce immediate but transient changes in cognitive and emotional functioning [8,9]. Evidence

indicates that AAE is associated with better executive control, although effects may vary by exercise parameters and participant characteristics [10]. Proposed mechanisms broadly include transient increases in arousal and modulation of prefrontal functioning, alongside short-term neuroendocrine and neurotrophic responses [9,11–13]. The neuroendocrine model highlights the role of acute hormonal fluctuations, and the neurotrophic factor hypothesis points to the release of brain-derived neurotrophic factor (BDNF), which promotes neural plasticity and cognitive resilience, thereby improving EF [11,14–16]. Taken together, these models suggest that AAE could influence both cognitive and emotional processes through multiple physiological pathways. Furthermore, the role of interoception, the nervous system's ability to perceive and interpret internal bodily signals (e.g., elevated heart rate or breathing during exercise), may also act as a critical mechanism linking acute physiological arousal to subsequent emotion regulation [9,17]. However, it is not a primary focus of the current study.

Despite the positive effects of AAE on EF, evidence suggests that its influence may differ across specific subcomponents [10]. Several studies have reported that AAE exerts stronger effects on inhibitory control than on working memory or cognitive flexibility, indicating that inhibitory control may be particularly sensitive to exercise-induced physiological changes [18,19]. However, findings from other studies provide different observations [9,20]. Browne et al. (2016) observed significant improvements in inhibitory control following a single bout of AAE [21]. Meta-analytic evidence likewise indicates that AAE yields benefits in both inhibition and working memory domains [10]. Nevertheless evidence is rather unclear and inconsistent about the exact mechanism. For instance, Çakaloğlu et al. (2025) noted heterogeneity in activation patterns among older adults despite behavioural gains in core EF components [20]. Moreover, Wang et al. (2024) found that while a brief bout of exercise improved inhibitory control and working memory performance, its effects on other cognitive tasks were negligible [22]. These mixed findings highlight the need for further research to clarify how AAE influences different aspects of EF and their potential relevance for emotion regulation [9].

Given the mixed findings on EF, it is important to extend the focus to emotion regulation, a related domain that relies on overlapping prefrontal mechanisms and directly contributes to mood disturbances in postmenopausal women [23]. Emotion regulation is crucial for mental health, with the ventrolateral prefrontal cortex (VLPFC) modulating emotional responses, the dorsolateral prefrontal cortex (DLPFC) supporting cognitive reappraisal and the subgenual anterior cingulate cortex (sgACC), integrating signals between prefrontal and limbic regions [17]. Disruptions in this network destabilize the balance between cognitive control and emotional reactivity, thereby increasing vulnerability to mood disturbances [24]. Cognitive reappraisal, an adaptive strategy for reinterpreting emotional stimuli, is particularly dependent on VLPFC and DLPFC activation, and enhancing these regions may represent a key pathway through which acute aerobic exercise strengthens emotion regulation [23,24]. Functional near-infrared spectroscopy (fNIRS) offers a suitable method to examine this possibility, as it enables non-invasive, real-time monitoring of prefrontal oxygenation [24]. This question is particularly relevant in postmenopausal women, in whom hormonal decline may affect prefrontal systems that support cognitive reappraisal. Yet, studies in postmenopausal women are scarce, and it remains unclear whether acute aerobic exercises is associated with changes in prefrontal activation during cognitive reappraisal in this population [17,24].

The aim of this study was to examine whether AAE is associated with improved emotion regulation in postmenopausal women, as reflected in subjective affect during cognitive reappraisal and task-evoked changes in oxygenated haemoglobin in the ventrolateral and dorsolateral prefrontal cortices measured using fNIRS.

2 Methods

2.1 Participants

Postmenopausal women were recruited through community health centres and online advertisements. Inclusion criteria required natural menopause (cessation of menstruation for at least 12 consecutive months), absence of psychiatric or neurological disorders, no history of major cardiovascular disease, and ability to perform moderate-intensity exercise safely. Exclusion criteria included hormone replacement therapy, current use of psychotropic medications, smoking, or musculoskeletal conditions preventing treadmill or cycling exercise.

A total of 780 women were screened. Of these, 102 met eligibility criteria and provided informed consent; participants were randomised to the exercise group (n = 50) or the sedentary control group (n = 49) using a computer-generated randomisation sequence prepared by a researcher not involved in enrolment or outcome assessment. Allocation was concealed until completion of baseline and pretest procedures, after which group assignment was revealed to implement the intervention (Fig. 1). Three participants did not accept the allocated condition (exercise n = 1; sedentary n = 2) and therefore did not receive the intervention. The present analyses were conducted in participants who completed the session and had usable behavioural and fNIRS data, yielding an analysed sample of 67 participants (exercise n = 32; sedentary n = 35). Baseline demographic and physiological measures in the analysed sample did not differ significantly between groups (Table 1). The study was conducted in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of Shanghai University of Sport (Approval No. 102772022RT056). All participants provided written informed consent prior to participation.

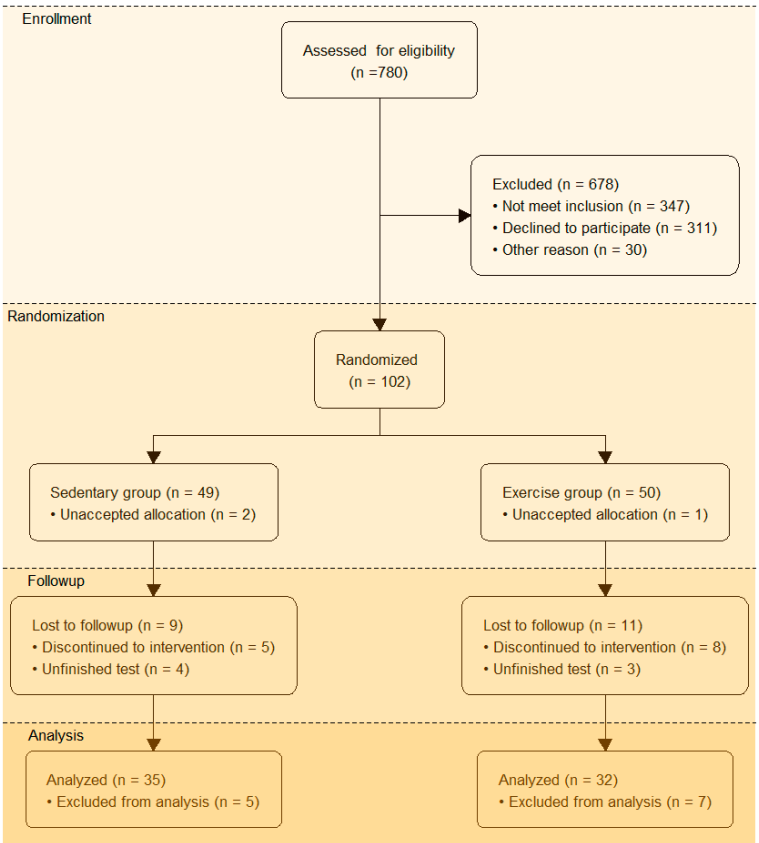

Figure 1: Participant flow diagram following the Consolidated Standards of Reporting Trials (CONSORT) guidelines.

Table 1: The baseline characteristics in this study.

	Sedentary (n = 35)	Exercise (n = 32)	p-Value
	Mean ± SD	Mean ± SD	
Age (years)	60.03 (±5.54)	59.06 (±5.29)	0.40
Height (cm)	158.57 (±4.92)	159.90 (±4.90)	0.28
Weight (kg)	61.08 (±12.64)	60.80 (±8.40)	0.94
Heart Rate (beats/min.)	82.91 (±4.92)	81.63 (±3.20)	0.11

Note: SD: Standard Deviation; cm: centimeter; kg: kilogram; min: minute.

2.2 Study Design and Procedure

The study adopted a randomised controlled design with two parallel arms: (i) acute aerobic exercise and (ii) sedentary control. Each participant attended a single experimental session. Because of the nature of the intervention, participants could not be blinded to group assignment. After baseline assessments, participants completed the pretest emotion regulation task while fNIRS recordings were acquired. The intervention phase followed immediately, consisting of either a bout of aerobic exercise (exercise group) or quiet sitting (sedentary group). Once the intervention was completed and heart rate had returned close to baseline levels (approximately 8–12 min after exercise), participants performed the post-test emotion regulation task with fNIRS recording. Subjective affect ratings were collected after each condition.

Exercise intervention group (Exercise group): Participants in the exercise group performed a 30-min session of moderate-intensity aerobic exercise on a cycle ergometer. Exercise intensity was prescribed at 50–75% of the individual's age-predicted maximum heart rate (HRmax = 220 − age) [25,26]. Heart rate was continuously monitored with a chest-strap monitor (Polar, Finland), and exercise commenced once participants reached 50% HRmax [27,28]. Resistance was adjusted to maintain the target range throughout the session. To ensure adherence, ratings of perceived exertion (RPE; Borg 6–20 scale) were recorded every 5 min, with a target of 12–14 ("somewhat hard") [26,29].

Control group (Sedentary group): Participants assigned to the sedentary group remained seated quietly in a comfortable chair for 30 min in the same laboratory environment. They were instructed not to engage in physical activity, reading, or emotionally stimulating tasks during this period. This control condition was designed to account for the effects of time and laboratory exposure while isolating the impact of acute aerobic exercise.

2.3 Experimental Measures

Emotion regulation task: The experimental task comprised four conditions: neutral viewing, negative viewing, negative reappraisal, and suppression [30]. A total of 120 images (30 per condition) were selected from the International Affective Picture System (IAPS) and validated Chinese emotional picture sets [31,32]. Neutral images depicted non-arousing objects or landscapes, while negative images depicted scenes of sadness, threat, or interpersonal conflict [33].

Each trial began with a fixation cross (2 s), followed by picture presentation (6 s). In the neutral and negative viewing conditions, participants were instructed to observe images naturally. In the reappraisal condition, they were asked to reinterpret the content of negative images to reduce emotional impact (e.g., imagining that the situation was staged or less harmful) [30]. In the suppression condition, participants were instructed to inhibit outward emotional expressions while viewing negative images [31,32]. After each trial, participants rated their subjective negative affect using a 7-point Likert scale (1 = none, 7 = very strong). Condition order was pseudorandomized and counterbalanced between participants.

fNIRS data acquisition: Cortical hemodynamic activity was measured using a continuous-wave functional near-infrared spectroscopy (fNIRS) system (NIRx Medical Technologies, NIRSport2, Germany) with wavelengths of 760 and 850 nm. The system included 8 light sources and 7 detectors arranged in a cap based on the international 10–20 system, yielding 20 measurement channels with a source–detector distance of 30 mm. Signals were sampled at 10.2 Hz [34,35].

Regions of interest (ROIs) included the left and right ventrolateral prefrontal cortex (VLPFC), left and right dorsolateral prefrontal cortex (DLPFC), frontopolar area (FPA), and orbitofrontal cortex (OFC). These regions have been consistently implicated in cognitive control and emotion regulation [36–38].

fNIRS preprocessing: Raw fNIRS signals were preprocessed using the Homer2/NIRS-SPM toolbox in MATLAB [39]. Channels with poor coupling, signal saturation, or excessive noise on visual inspection were excluded. Motion artifacts were corrected using spline interpolation and wavelet filtering [40,41]. Data were band-pass filtered at 0.01–0.2 Hz to remove slow drifts and high-frequency noise. Changes in oxygenated haemoglobin (HbO2) concentration were calculated using the modified Beer–Lambert law with a differential path length factor of 6.0 [42]. Data were baseline-corrected relative to the 2 s pre-stimulus interval. Participants with insufficient usable channels for ROI-level analysis after preprocessing were excluded from the final fNIRS analyses. For each participant, mean HbO2 values were extracted by condition and ROI.

2.4 Statistical Analysis

Analyses were conducted using a complete-cases approach (i.e., participants with complete pre–post behavioural ratings and usable fNIRS data after quality control); intention-to-treat approach was not applied, because unusable fNIRS recordings resulted in missing primary neuroimaging outcomes that could not be validly imputed. Behavioural data were analysed using Statistical Package for the Social Sciences (Version 26.0; IBM Corp., Armonk, NY, USA). Descriptive statistics were used to report sample characteristics. Continuous variables were presented as Mean + Standard Deviation (SD). A 2 (group: exercise vs. sedentary) × 2 (time: pre vs. post) × 4 (strategy: neutral, negative, reappraisal, suppression) mixed-design Analysis of Variance (ANOVA) was performed on subjective affect ratings. Assumptions of normality were checked using the Shapiro–Wilk test and visual inspection of residual distributions. Sphericity for repeated-measures factors with more than two levels was assessed using Mauchly's test; where violated, Greenhouse–Geisser corrections were applied. Task validity was evaluated by comparing ratings of neutral and negative images at baseline. Post hoc analyses were Bonferroni-corrected. fNIRS data were analysed separately for each Region of Interest (ROI). HbO2 concentration values were submitted to 2 (group) × 2 (time) mixed ANOVAs. To limit Type I error, behavioural outcomes were analysed within a single mixed-design ANOVA, and post hoc comparisons were Bonferroni-corrected. For fNIRS, ROI-specific ANOVAs were conducted to characterise regional response patterns; no formal correction for multiple ROI comparisons was applied, and these findings were therefore interpreted cautiously. Significant interactions were further explored using simple effect analyses (pre vs. post within each group). Effect sizes were reported as partial eta-squared (η^2) for ANOVAs and Cohen's d for pairwise contrasts. Ninety-five percent confidence intervals (95% CI) were calculated where appropriate. Statistical significance was set at $p < 0.05$ (two-tailed) for all analyses.

3 Results

At baseline, no significant differences were observed between the exercise group ($n = 32$) and the sedentary group ($n = 35$) in demographic or physiological variables, including age, height, weight, and resting heart rate (all $p > 0.05$), confirming comparability between groups (Table 1).

A mixed ANOVA on pretest ratings confirmed task validity, showing a significant main effect of emotion regulation ($F(3, 195) = 13.73$, $p < 0.001$); neutral viewing ratings were lower than negative viewing, negative reappraisal, and suppression (all $p < 0.001$) (Table 2). No significant main effect of group or Group × Emotion Regulation interaction was observed. These findings confirm that the task instructions and emotional picture stimuli successfully induced distinct emotional states across conditions.

Table 2: Summary statistics of emotion regulation after acute exercise.

Time	Emotion Regulation	Sedentary (n = 35)	Exercise (n = 32)
		Mean ± SD	Mean ± SD
Pre	Neutral	1.54 (±0.43)	1.55 (±0.44)
	Negative	2.38 (±0.61)	2.15 (±0.53)
	Reappraisal	2.07 (±0.57)	1.74 (±0.45)
	Suppression	2.09 (±0.58)	1.78 (±0.46)
Post	Neutral	1.63 (±0.47)	1.51 (±0.41)
	Negative	2.29 (±0.60)	2.09 (±0.52)
	Reappraisal	2.30 (±0.60)	1.78 (±0.46)
	Suppression	2.34 (±0.62)	1.86 (±0.47)

Note: Effect sizes for the main ANOVA effects and key pairwise comparisons are reported in the text. ANOVA: analysis of variance; SD: Standard Deviation.

A 2 (group: exercise vs. sedentary) × 2 (time: pre vs. post) × 4 (strategy: neutral viewing, negative viewing, negative reappraisal, suppression) mixed ANOVA revealed significant main effects of emotion regulation, group, and time (all $p < 0.05$), as well as a significant Group × Emotion Regulation interaction ($F(3, 195) = 7.18$, $p < 0.001$). Post hoc analyses indicated that, following the intervention, the exercise group reported significantly lower negative affect scores during both reappraisal and suppression compared with the sedentary control group (all $p < 0.001$), with no group differences for neutral or negative viewing (Fig. 2).

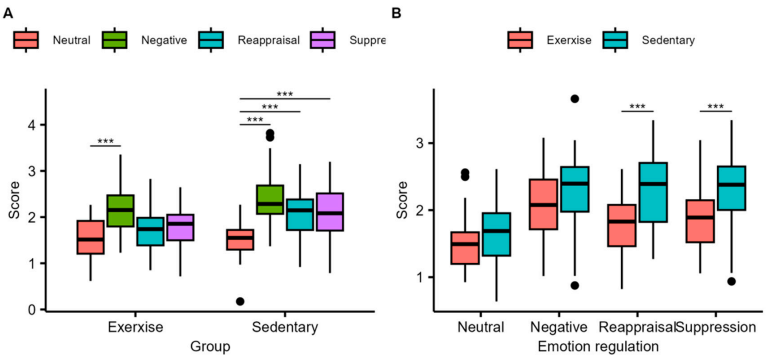

Figure 2: Subjective affect ratings across emotion-regulation conditions and groups. Boxplots show affect rating scores (unitless) for neutral viewing, negative viewing, cognitive reappraisal, and suppression in the exercise and sedentary control groups. Panel (**A**) displays scores by group, and panel (**B**) displays scores by condition. Higher scores indicate more negative affect. Boxes represent the interquartile range (IQR) with the median line; whiskers extend to 1.5 × IQR; points indicate outliers. Horizontal brackets denote statistically significant differences (***$p < 0.001$).

Analysis of HbO2 during reappraisal showed significant Group × Time interactions in the left VLPFC ($F(1, 64) = 20.89$, $p < 0.001$, $\eta^2 = 0.246$), right VLPFC ($F(1, 64) = 4.29$, $p = 0.042$, $\eta^2 = 0.063$), and left DLPFC ($F(1, 64) = 23.41$, $p < 0.001$, $\eta^2 = 0.268$) (Table 3; Fig. 3). Simple effect indicated no group differences at pretest,

with significant pre–post changes in the exercise group but not in the sedentary group. No significant effects were observed in the right DLPFC, frontopolar area, or orbitofrontal cortex (all $p \geq 0.05$).

Table 3: Summary statistics of region of interest in emotion regulation after acute exercise.

Emotion Regulation	Region of Interest	Sedentary (n = 35)		Exercise (n = 32)	
		Pre-Test (Mean ± SD)	Post-Test (Mean ± SD)	Pre-Test (Mean ± SD)	Post-Test (Mean ± SD)
Neutral	lVLPFC	−4.35 (±8.48)	−6.04 (±7.94)	−4.75 (±10.34)	−0.77 (±2.05)
	rVLPFC	−3.27 (±8.16)	−7.13 (±8.77)	−6.56 (±11.72)	−0.56 (±3.89)
	lDLPFC	−2.46 (±6.48)	−6.38 (±23.93)	−3.98 (±7.89)	−0.05 (±2.26)
	rDLPFC	−3.58 (±6.12)	−6.74 (±9.80)	−4.31 (±7.23)	−0.95 (±16.91)
	FPA	−4.64 (±6.66)	−6.75 (±8.61)	−6.09 (±9.58)	−5.27 (±20.84)
	OFC	−6.55 (±7.84)	−7.87 (±8.60)	−6.84 (±12.28)	−5.30 (±29.83)
Negative	lVLPFC	11.89 (±8.46)	8.36 (±5.22)	10.23 (±8.07)	2.09 (±1.51)
	rVLPFC	11.55 (±7.87)	15.60 (±33.21)	12.85 (±11.08)	2.56 (±2.31)
	lDLPFC	10.39 (±6.70)	15.18 (±26.70)	9.63 (±6.04)	2.03 (±1.64)
	rDLPFC	11.32 (±6.51)	10.92 (±8.42)	9.42 (±6.51)	9.84 (±6.85)
	FPA	10.26 (±6.32)	9.63 (±7.47)	11.03 (±9.55)	11.74 (±12.29)
	OFC	13.55 (±15.21)	12.82 (±10.67)	13.35 (±15.43)	14.05 (±15.26)
Reappraisal	lVLPFC	10.73 (±7.64)	10.93 (±7.28)	9.38 (±7.00)	1.86 (±1.14)
	rVLPFC	11.75 (±5.83)	11.97 (±8.96)	9.51 (±9.07)	4.00 (±8.65)
	lDLPFC	9.00 (±5.79)	9.77 (±6.65)	8.32 (±5.19)	1.61 (±1.39)
	rDLPFC	9.58 (±5.28)	11.28 (±10.09)	9.42 (±6.86)	7.66 (±5.03)
	FPA	10.04 (±7.24)	9.75 (±8.90)	11.21 (±10.40)	12.11 (±19.19)
	OFC	12.52 (±12.16)	12.56 (±13.56)	13.08 (±15.79)	17.20 (±30.03)
Suppression	lVLPFC	2.50 (±5.83)	2.20 (±4.15)	2.74 (±7.63)	0.34 (±0.73)
	rVLPFC	2.12 (±4.13)	3.84 (±7.15)	2.75 (±7.65)	0.57 (±1.33)
	lDLPFC	1.91 (±3.82)	3.42 (±7.24)	2.23 (±5.38)	0.26 (±0.40)
	rDLPFC	1.84 (±3.17)	2.37 (±4.60)	1.91 (±3.81)	1.32 (±2.22)
	FPA	1.50 (±2.99)	2.23 (±3.41)	3.39 (±8.44)	1.74 (±2.95)
	OFC	2.31 (±5.18)	2.23 (±4.14)	4.38 (±14.24)	2.54 (±5.51)

Values presented mean (±standard deviation). VLPFC: Ventrolateral prefrontal cortex, DLPFC: Dorsolateral prefrontal cortex, FPA: Frontopolar prefrontal cortex, OFC: Orbitofrontal cortex, r: right, l: left. SD: Standard Deviation.

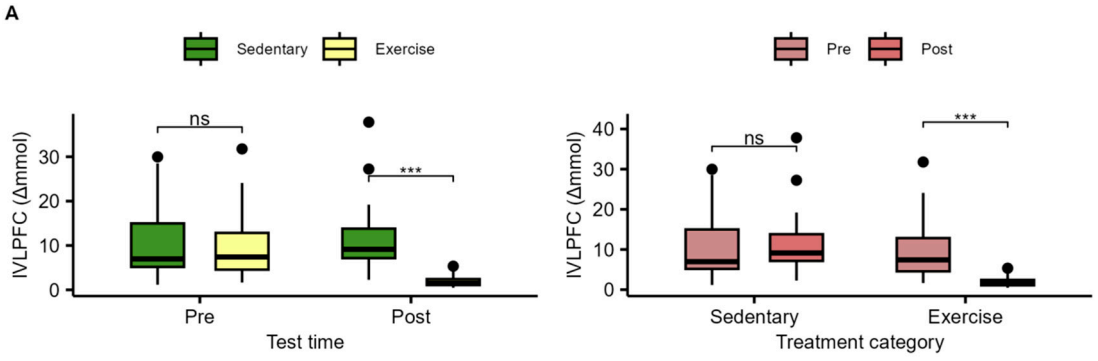

Figure 3: *Cont.*

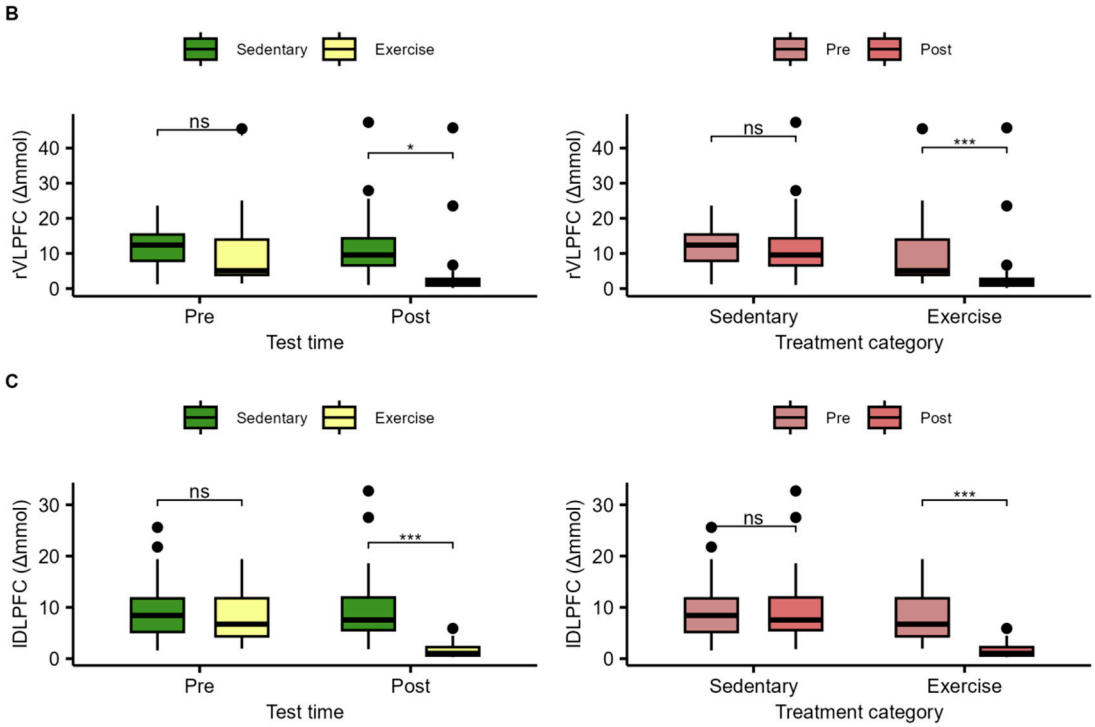

Figure 3: Comparison of HbO2 in lVLPFC, rVLPFC and lDLPFC by time and treatment category. Boxplots show changes in HbO2 concentration (Δmmol) in (**A**) left ventrolateral prefrontal cortex (lVLPFC), (**B**) right ventrolateral prefrontal cortex (rVLPFC), and (**C**) left dorsolateral prefrontal cortex (lDLPFC) at pre-test and post-test in the exercise and sedentary control groups. For each ROI, the left panel presents HbO2 by test time (Pre vs. Post) within each group, and the right panel presents HbO2 by treatment category (Sedentary vs. Exercise) within each time point. Boxes represent the interquartile range (IQR) with the median line; whiskers extend to 1.5 × IQR; points indicate outliers. Brackets indicate pairwise comparisons; ns = not significant; $^{*}p < 0.05$; $^{***}p < 0.001$. Abb: HbO2: oxygenated haemoglobin; lVLPFC: left ventrolateral prefrontal cortex; rVLPFC: right ventrolateral prefrontal cortex; lDLPFC: left dorsolateral prefrontal cortex.

4 Discussion

The present study examined acute effects of moderate-intensity aerobic exercise on emotion regulation and prefrontal activation in postmenopausal women using fNIRS. There are two major findings of this study. First, women in the exercise group reported significantly lower negative affect ratings during cognitive reappraisal and suppression tasks compared with the sedentary control group. Second, fNIRS results demonstrated significant exercise-related changes in HbO_2 responses in the bilateral VLPFC and left DLPFC during reappraisal after exercise. Together, these findings suggest that even a single bout of aerobic exercise is associated with better emotion regulation in postmenopausal women, reflected in lower negative affect and reduced prefrontal haemodynamic demand during reappraisal.

The findings of this study align with, and extend, prior research reporting the benefits of AAE on mood and cognition [8,9]. Numerous studies in younger and mixed-age adults have shown that AAE is associated with higher EF, reduces negative affect, and was associated with prefrontal activation during cognitive tasks [10,11,21,43]. The present study adds to this body of evidence by demonstrating similar acute associations of AAE in postmenopausal women, a group understudied in exercise neuroscience, even though they are at a higher risk for mood disturbances [1,2,6]. While most previous neuroimaging studies

relied on fMRI, our use of fNIRS shows that exercise-induced increases in prefrontal activation can also be detected in more naturalistic task settings [24,35,43]. More importantly, by demonstrating altered VLPFC and DLPFC activity during reappraisal, we provide direct evidence that exercise is associated with neural circuits most critical for adaptive emotion regulation [23,24,44]. In addition, our findings highlight the importance of considering age and hormonal status when interpreting the effects of AAE on mood and cognition [3,4]. Evidence from younger populations suggests broad benefits of AAE across multiple EF sub-domains, but the present results showed that in postmenopausal women, benefits may be more selective, potentially involving regions that may be hormonal decline [10,13,33]. This suggests that the neural effects of exercise may vary across the lifespan and underscores the value of studying specific populations rather than generalizing the findings of studies on younger populations [19,20].

The behavioural results indicate that AAE was associated with lower negative emotional ratings, particularly when women employed cognitive reappraisal and suppression strategies [30–32]. These findings are especially relevant given the heightened risk of mood disturbances in postmenopausal women [1,2,5]. Declining estrogen levels are associated with reduced serotonergic and dopaminergic activity, contributing to emotional instability [45,46]. At the same time, psychosocial stressors such as caregiving responsibilities, occupational transitions, and retirement-related changes further exacerbate vulnerability to anxiety and depression [7,47]. The observed reduction in negative affect following AAE therefore suggests that exercise may temporarily buffer against these biological and psychosocial risk factors.

The pattern of findings for reappraisal performance is particularly noteworthy. Postmenopausal women often display reduced flexibility in reframing negative experiences due to diminished prefrontal efficiency and age-related cognitive decline [3,13,46]. Changes following exercise may represent a potential mechanism supporting adaptive coping [23,24]. Improvements in suppression tasks further indicate that AAE was associated with inhibitory control, allowing for greater modulation of emotional expression [19,30,32]. Although suppression is considered less adaptive than reappraisal, it may provide immediate relief in stressful contexts, highlighting the multifaceted benefits of exercise [30,48].

At the neural level, significant Group × Time interactions were observed in the left and right VLPFC and left DLPFC during reappraisal. These findings align with the established roles of these regions in emotion modulation and cognitive control [49,50]. For postmenopausal women, this is especially relevant, as estrogen decline is associated with reduced prefrontal plasticity and dopaminergic modulation [51,52]. The observed changes may reflect compensatory mechanisms in the acute post-exercise period.

The left DLPFC response underscores its role in adaptive, approach-oriented strategies such as reappraisal, consistent with prior evidence of hemispheric specialization [53]. The absence of significant changes in the right DLPFC, frontopolar areas (FPA), and OFC highlights the regional specificity of the effect of exercise. The null OFC finding may reflect both functional specificity, reappraisal relies more on lateral prefrontal control than OFC-mediated valuation [49,50], and lower fNIRS sensitivity in inferior frontal regions (e.g., anatomical constraints and extracerebral signal) [35]. While somewhat surprising, this failure to show a significant effect on the OFC in itself suggests that further research is necessary to fully delineate the boundaries of exercise-induced neural changes. Rather than enhancing activation globally, AAE appears to selectively modulate the most critical networks for cognitive reappraisal.

Several mechanisms may explain these benefits. Physiologically, acute exercise elevates catecholamines such as dopamine and norepinephrine, which can transiently improve prefrontal efficiency [11,12]. Exercise also increases brain-derived neurotrophic factor (BDNF), enhancing synaptic plasticity and cognitive resilience, processes that may counteract declines linked to menopause [15,16]. Psychologically, exercise may reduce perceived stress, improve self-efficacy, and enhance attentional control [54]. For postmenopausal

women, these changes may facilitate efficient engagement with adaptive regulation strategies such as reappraisal. However, these mechanistic interpretations are speculative, as catecholamines and BDNF were not measured.

These findings have important clinical and public health implications. Approximately one in three postmenopausal women experience mood disturbances [1,2], and pharmacological treatments such as hormone therapy or antidepressants are limited by side effects, contraindications, and adherence issues [47,51]. Therefore, AAE represents a safe, accessible, and cost-effective intervention that can be easily integrated into daily routines. The demonstration that even a single exercise session reduces negative affect and was associated with prefrontal response suggests that exercise could serve not only as a preventive measure but also as an immediate coping tool for acute emotional distress. Beyond individual benefits, promoting exercise in this population may also reduce healthcare costs and improve quality of life at the societal level. Considering the growing size of the global postmenopausal population, lifestyle-based interventions such as AAE could play a key role in reducing the burden of depression and anxiety while simultaneously improving physical health outcomes such as cardiovascular function and metabolic health [3]. However, these findings reflect acute effects, and the extent to which they translate into sustained improvements remains to be established.

This study has a few limitations. First, the sample size is relatively small given the statistical treatments used, which may constrain statistical power and generalizability. To better control for inter-individual variability and robustly validate these findings, future research should consider employing a randomised cross-over design. Because analyses were based on complete cases with usable fNIRS data, selection bias is possible if attrition or data loss was not random. An a priori power calculation was not conducted due to limited comparable fNIRS effect-size data in this population; effect sizes and 95% confidence intervals are therefore reported. The use of a single exercise session precludes conclusions about long-term effects. We also did not collect hormonal measures (e.g., oestradiol), limiting our ability to examine whether hormonal status moderated behavioural or neural responses to exercise. The fNIRS, while useful for assessing cortical hemodynamics, cannot capture subcortical regions such as the amygdala, which play essential roles in emotion regulation [35]. Finally, the absence of follow-up assessments limits the ability to determine whether acute benefits translate into enduring clinical improvements.

Future research should examine the dose–response relationship of exercise intensity and duration in postmenopausal women and explore whether repeated sessions yield cumulative benefits [12,18]. Studies should also incorporate hormonal measures and genetic markers of neuroplasticity to clarify individual differences in responsiveness. Combining fNIRS with other neuroimaging methods could provide a more comprehensive understanding of connectivity between prefrontal and limbic systems [34,35]. Moreover, future investigations should adopt multi-center and cross-cultural designs to allow generalizability across diverse populations. Given the variations in lifestyle, healthcare systems, and sociocultural expectations for women, cross-national studies could help identify contextual factors that shape the impact of AAE on emotion regulation in midlife and later life. Such research would strengthen the ecological validity of exercise interventions and support the development of culturally sensitive health policies.

5 Conclusion

In healthy postmenopausal women, a single bout of moderate-intensity aerobic exercise was associated with lower negative affect during cognitive reappraisal and suppression. fNIRS measures indicated significant group-by-time effects in lateral prefrontal regions during reappraisal in the immediate post-exercise period. These findings are limited to acute effects following one exercise session. Future

longitudinal studies are needed to determine whether repeated exercise produces sustained and clinically meaningful benefits.

Acknowledgement: Not applicable.

Funding Statement: The author received no specific funding for this study.

Availability of Data and Materials: The data that support the findings of this study are available from the Corresponding Author (Chang Xu) upon reasonable request.

Ethics Approval: The study was conducted in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of Shanghai University of Sport (Approval No. 102772022RT056). All participants provided written informed consent prior to participation.

Conflicts of Interest: The author declares no conflicts of interest.

Nomenclature

fNIRS	Functional near-infrared spectroscopy
AAE	Acute aerobic exercise
EF	Executive function
VLPFC	Ventrolateral prefrontal cortex
DLPFC	Dorsolateral prefrontal cortex
sgACC	Subgenual anterior cingulate cortex

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