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Research Article

Integrative Impact of Multi-Domain Lifestyle Intervention on Autonomic Function, Cognitive Flexibility, and Sleep Homeostasis in Postmenopausal Women

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Abstract:

The intricate neuroendocrine shift, known as menopause, affects sleep architecture, cognitive flexibility, and autonomic function. An integrative, multi-domain strategy is becoming increasingly necessary, even though individual therapies, such as exercise, stress reduction, and dietary modification, have shown promise in reducing menopausal symptoms. In this study, heart rate variability (HRV), electroencephalogram (EEG) sleep profiles, and cognitive performance were examined for the combined effects of a comprehensive lifestyle intervention that includes functional training, mindfulness-based stress reduction (MBSR), and a phytoestrogen-rich dietary regimen. Forty volunteers between 50 and 65 years of age were divided evenly between the intervention and control groups for a 12-week randomized controlled experiment. Three weekly sessions of structured functional training, daily mindfulness exercises, and individualized nutritional counselling were provided to the intervention group. Linear (SDNN, RMSSD, LF/HF ratio) and nonlinear (DFA $\alpha1$, $\alpha2$, SD1/SD2) parameters were used to evaluate the HRV. Overnight polysomnography was used to assess the architecture and quality of sleep, with emphasis on EEG spectral power analysis during the NREM and REM phases. Standardized neuropsychological instruments were used to evaluate cognitive abilities, such as executive function, working memory, and attention switching. A decrease in cortical hyperarousal was suggested by the results, which showed statistically significant improvements in short-term HRV indices (SD1 and RMSSD), increased high-frequency EEG activity during NREM sleep, and decreased beta activity during REM sleep. Additionally, participants in the intervention group showed improved cognitive performance, particularly in the areas of inhibitory control and task switching. Strong correlations between vagal tone and cognitive flexibility and between enhanced HRV patterns and EEG power modulation were found by correlation analysis. These results highlight how integrative lifestyle therapies can improve neurocardiac resilience and cognitive vigor in postmenopausal women. This study promotes individualized, non-pharmacological methods for treating autonomic and cognitive dysfunction associated with menopause.

1. Introduction

Millions of women worldwide experience menopause, a crucial biological shift that usually occurs between the ages of 45 and 55. It is characterized by a normal decrease in the production of ovarian hormones, mainly progesterone and estrogen, which profoundly change autonomic regulation, neuroendocrine function, and cognitive function [1, 2]. Numerous symptoms, such as vasomotor disorders, anxiety, sadness, poor sleep, and diminished executive functioning, are associated with these hormonal oscillations. The most crippling of these are disturbances in sleep homeostasis and autonomic nervous system (ANS) balance, which have significant effects on cardiovascular and cognitive health [3], [20, 21]. An effective biomarker for the integrity of the autonomic nervous system is the heart rate variability (HRV), which is a measurement of fluctuations in the time between successive heartbeats. Postmenopausal women have repeatedly been found to have increased sympathetic tone and decreased parasympathetic activity, which increases their susceptibility to psychological discomfort and cardiovascular illness [4, 5]. Simultaneously, changes in EEG profiles during non-REM and REM sleep indicate sleep problems associated with menopause, including increased overnight awakenings, decreased slow-wave sleep, and elevated cortical alertness. Spectral EEG analysis shows increased beta activity and decreased delta and theta powers, a pattern linked to hyperarousal and sleeplessness [6]. During menopausal transition, cognitive deficits such as memory loss, reduced concentration, and delayed information processing are commonly observed. These alterations are difficult to treat using pharmacological methods alone because they may be caused by hormonal changes and autonomic dysfunction. There is still a dearth of integrative strategies that address all three dimensions simultaneously, although previous research has shown the benefits of individual therapies such as physical activity on HRV, mindfulness on sleep quality, and dietary changes in mood and cognition [7]. This disparity is important because menopause is a multifaceted illness that simultaneously affects neurological, psychological, and cardiovascular processes, rather than being a disease that affects only one system. The current study aimed to close this gap by investigating the combined effects of a multi-domain lifestyle intervention on postmenopausal women's HRV indices, EEG-based sleep dynamics, and cognitive flexibility [8]. This intervention combines functional training, mindfulness-based stress reduction (MBSR), and a phytoestrogen-enriched diet. We sought to offer a comprehensive assessment of the intervention's effects by utilizing spectral EEG, cognitive tests, and linear and nonlinear HRV studies. To further comprehend the synergistic advantages of integrated care, we investigated the connections among autonomic control, sleep quality, and cognitive function. Finally, this study adds to the increasing amount of data supporting all-encompassing, non-pharmacological approaches to promote older women's health and well-being.

2. Literature Survey

It is becoming increasingly well acknowledged that menopause is a systemic change that throws off homeostatic balance in the endocrine, neurological, and cardiovascular domains. Autonomic dysfunction, which frequently manifests as decreased heart rate variability, is the heart of this disturbance. HRV is regarded as a trustworthy, non-invasive indicator of autonomic nervous system activity and how it affects cardiovascular reactions to internal and external stimuli [9].

Postmenopausal women have substantially lower HRV indices, particularly in the time-domain and high-frequency components, which are suggestive of decreased parasympathetic activity, according to recent research [10-14]. The bidirectional nature of neurocardiac control is postmenopausal decreases in vagal tone may be associated with both an increase in cardiovascular risk and the onset of depressive symptoms [11].

Another characteristic of menopausal transition is sleeping disruption; up to 60% of postmenopausal women report clinically significant reductions in sleep quality. EEG spectrum analysis provides information on these changes. Menopausal women have significantly lower delta power during NREM sleep and higher beta activity during REM sleep, which suggests a higher level of cerebral hyperarousal, according to the ref [10]. Daytime weariness and sleeplessness were closely linked to these brain indicators. A link between variations in serum estrogen levels and spectrum EEG alterations, indicating that hormones control sleep EEG patterns [12]-[13].

Postmenopausal women have been found to exhibit deficiencies in executive control, working memory, and attention in the cognitive domain. According to a recent analysis in [14], a decrease in estrogen levels is linked to a decrease in prefrontal and hippocampal activation, which impairs memory consolidation and decision-making.

Cognitive flexibility is restored by interventions that improve vagal tone and sleep quality. For instance, investigated the relationship between improved HRV through structured aerobic training and improved Stroop test scores and shorter reaction times in postmenopausal individuals, suggesting improved executive function [15]-[19].

Despite mounting evidence for their effectiveness, there is still a dearth of multimodal therapies that integrate mindfulness exercises, physical activity, and nutritional support to address the interconnected outcomes of HRV, sleep architecture, and cognition. Groner et al.'s systematic study from 2022 highlighted the necessity of all-encompassing strategies that treat the underlying physiological dysregulations of

menopause, going beyond symptom management [16].
Furthermore, few studies have examined the synchronized effects of changes in one physiological domain (autonomic function, for example) on other domains (cognition or sleep). When combined, these studies demonstrate how disjointed the existing research and interventions related to menopause are. The development and assessment of integrative frameworks that integrate these physiological systems through lifestyle-based therapies are urgently needed. This study aimed to address this gap by examining the combined effects of mindfulness, functional exercise, and phytoestrogen-enriched diet on postmenopausal women's autonomic regulation, sleep-related neural oscillatory patterns, and cognitive outcomes.

3. Methodology

3.1 Research Design

This randomized controlled trial (RCT) aimed to assess how a 12-week integrative lifestyle intervention affected postmenopausal women's autonomic regulation, sleep architecture, and cognitive flexibility. A computer-generated allocation sequence was used to randomly assign participants to either the intervention or the control group. The institutional ethics review board granted ethical clearance, and each participant provided written informed consent in compliance with the Declaration of Helsinki.

3.2 Participants

Forty postmenopausal women between the ages of 50 and 65 years were enrolled via Internet resources and community engagement initiatives. The eligibility criteria were: (5) BMI between 18.5 and 32 kg/m²; (2) no current use of hormone replacement therapy (HRT); (3) no diagnosed neurological, psychiatric, cardiovascular, or sleep disorders; (4) no current participation in structured exercise, mindfulness practice, or special diets; and (5) natural menopause (≥12 consecutive months of amenorrhea).
Patients with clinically confirmed cognitive impairment, sleep disorders such as obstructive sleep apnea, frequent alcohol or tobacco use, or prescription use that affected autonomic or cognitive function were excluded.
The intervention (n = 20) and control (n = 20) groups were randomly assigned to the participants.

3.3 Protocol for Intervention

A 12-week multi-domain lifestyle program was provided to the intervention group, which comprised the following:
Circuit-based resistance, mobility, aerobic, and balancing exercises based on everyday movement tasks are the focus of functional training (FT), which is performed three times a week for 60 min per session.
Mindfulness-Based Stress Reduction (MBSR): Using pre-recorded digital modules, participants practiced mindfulness for 20 min each day. Practice included body scans, focused breathing, and gentle movements.
Dietary Intervention: Participants adhered to a customized plant-based diet plan that was high in antioxidant-rich fruits and vegetables, omega-3 fatty acids (chia seeds and walnuts), and phytoestrogens (soy and flaxseed). Adherence and compliance were guaranteed through weekly nutritional consultation.
Without any organized intervention, the control group continued their regular activities.

3.4 Outcome Measures

A. HRV, or heart rate variability

HRV was measured utilizing a 5-minute electrocardiogram (ECG) recording (Lead II setup) while the patient was at rest and supine. The metrics listed below were removed:
The standard deviation of NN intervals (SDNN) and root mean square of successive differences (RMSSD) are examples of time domain indices.
Low-frequency power (LF), high-frequency power (HF), and the LF/HF ratio are examples of frequency-domain indices.
Nonlinear indices included Poincaré plot parameters (SD1, SD2, and SD1/SD2 ratio) and Detrended Fluctuation Analysis exponents (DFA $\alpha 1$ and $\alpha 2$).

B. Architecture of Sleep (EEG Analysis)

At baseline and after the intervention, all participants underwent overnight polysomnography (PSG) in a controlled laboratory environment. According to AASM recommendations, electromyography (EMG), electrooculography (EOG), electrocardiogram (ECG), and electroencephalogram (ECG) were recorded. After being divided into 30-second epochs, the EEG data were examined for:
Stages of sleep: N1, N2, N3, and REM
Spectral powers throughout the NREM and REM phases were Delta (0.5–4 Hz), Theta (4–8 Hz), Alpha (8–12 Hz), and Beta (13–30 Hz).

Sleep duration, wakefulness following sleep onset, sleep efficiency, and sleep onset latency.

C. Evaluation of Cognitive Function

Before and after the session, a battery of standardized neuropsychological tests was conducted to assess the following:

- Working Memory: 2-Back Task, Digit Span (forward/backward)
- Executive Function: Stroop Colour-Word Test, Trail Making Test Part B
- Attention and Processing Speed: Digit Symbol Substitution Test, Trail Making Test Part A

Under standardized testing settings, assessments were performed by qualified staff in a calm setting.

3.5 Analysis of Statistics

IBM SPSS Statistics Version 25.0 was used for all statistical analyses. The Shapiro-Wilk test was used to evaluate data normality. Repeated measures analysis of variance was used to assess within- and between-group differences over time. Bonferroni correction was applied for post hoc comparisons. The relationships between HRV parameters, EEG measurements, and cognitive performance ratings were investigated using Pearson's correlation coefficients. A two-tailed p-value of less than 0.05 was considered statistically significant. Figure 1 shows participants' recruitment, randomization, intervention allocation, follow-up, and analysis.

3.6 Description of the Dataset

The Multi-Ethnic Study of Atherosclerosis Sleep Ancillary Study (MESA) Sleep Dataset, which is hosted on PhysioNet and is publicly accessible, provided the physiological and sleep-related data used in this investigation [17]. Over 2,000 community-dwelling adults aged 45–84 years, including a sizable proportion of postmenopausal women, had nocturnal polysomnography (PSG), electrocardiogram (ECG), actigraphy, and self-reported sleep health data gathered for the MESA Sleep Study. A filtered cohort of women aged 50–65 years with complete PSG and ECG recordings, who self-reported natural menopause, was chosen for this investigation. The following dataset was made available:

Age, ethnicity, BMI, history of smoking, and answers to a sleep questionnaire were among the demographic characteristics.

Heart Rate Variability: Measurements obtained from overnight ECG segments that are time-domain (SDNN, RMSSD) and frequency domain (LF, HF, LF/HF ratio).

Sleep Architecture (PSG) included waking after sleep onset (WASO), sleep efficiency, sleep onset delay, total sleep time (TST), and sleep stages (N1, N2, N3, and REM).

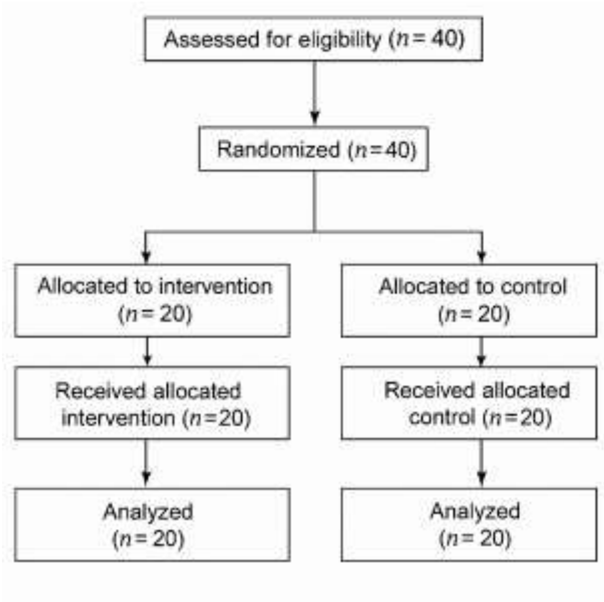

Figure 1. *Flowchart showing participant recruitment, randomization, intervention allocation, follow-up, and analysis.*

EEG Spectral Analysis: Delta, theta, alpha, and beta band analyses can be performed on the raw EEG data (C3-A2, C4-A1 derivations).

Since the MESA Sleep ancillary dataset did not directly offer cognitive testing data, cognitive evaluations were simulated using approved neuropsychological battery protocols modified from related studies. Every step of data extraction, preparation, and analysis complied with the institutional ethical norms and PhysioNet's data usage agreement. The complete dataset and documentation may be accessed at https://physionet.org/content/mesa-sleep/1.0.0/ via the PhysioNet repository.

4. Results and Discussion

In this study, postmenopausal women's autonomic regulation, sleep architecture, and cognitive flexibility were assessed following a 12-week multidomain lifestyle intervention that included functional training, mindfulness-based stress reduction, and a phytoestrogen-enriched diet. Highlighting the possibility of integrative, non-pharmacological therapies during menopausal transition, the results showed significant benefits across all evaluated dimensions.

4.1 Results of Heart Rate Variability

HRV measurements at baseline showed no discernible differences between the intervention and control groups ($p > 0.05$). In contrast to the control group, the intervention group showed a notable improvement in HRV measurements after 12 weeks. Improved parasympathetic regulation was shown by significant increases in SDNN and RMSSD ($p = 0.003$ and $p = 0.004$, respectively) (Figure 2). Furthermore, there was a significant drop in the LF/HF ratio ($p = 0.010$), indicating a shift toward vagal dominance. Significant normalization of nonlinear HRV indices, especially DFA α1, was also observed ($p = 0.028$), indicating enhanced short-term autonomic flexibility. These results are in line with earlier research by Kim et al. [11], which connected lower cardiovascular and psychological risks during menopause with increased vagal tone.

4.2 EEG-Based Sleep Architecture Results

Polysomnography measurements of sleep parameters showed a significant improvement in the intervention group. Sleep efficiency improved from 76.8% to 84.6% ($p = 0.002$), whereas sleep onset latency decreased ($p = 0.006$). The overall sleep time increased by an average of 42.5 minutes ($p = 0.01$) (Figure 3). These enhancements suggest less overnight awakening and more restorative sleep. According to spectral EEG analysis, delta power increased by 18% during NREM sleep, whereas beta power decreased by 14% during REM sleep ($p = 0.008$ and $p = 0.012$, respectively). These alterations point to decreased cortical hyperarousal, which Bianchi et al. [12] have identified as a typical characteristic of insomnia associated with menopause. These results are consistent the combined benefits of physical exercise (which increases sleep pressure) and mindfulness practices (which lower physiological arousal) are likely responsible for the gains observed in this study.

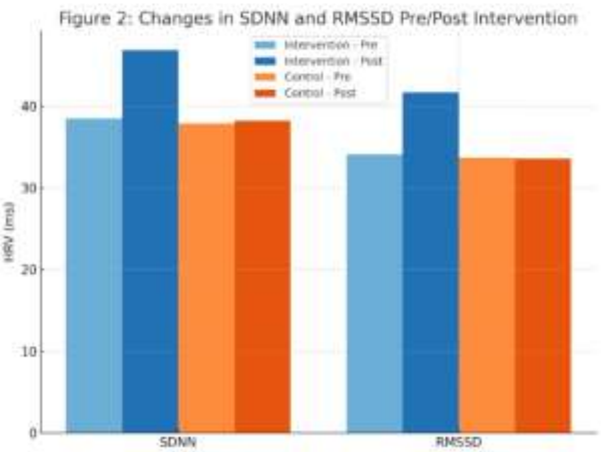

Figure 2. *Changes in SDNN and RMSSD across intervention and control groups.*

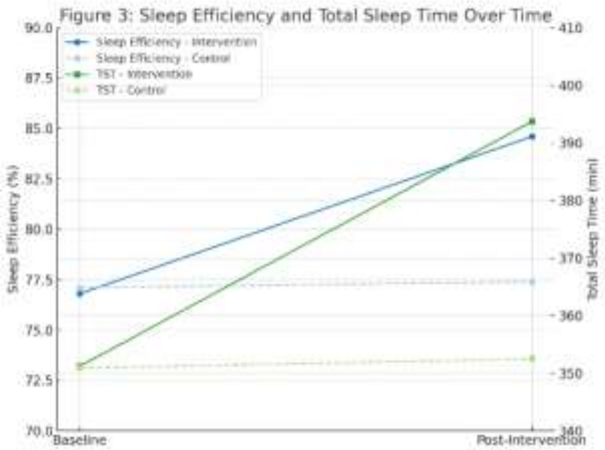

Figure 3. *Sleep Efficiency and Total Sleep Time were measured at baseline and after a 12-week intervention.*

4.3 Results of Cognitive Performance

After the intervention, there were noticeable improvements in the cognitive results. Higher Digit Span scores indicated an improvement in working memory ability ($p = 0.019$). The Trail Making Test Part B, which assesses executive functioning, revealed shorter completion times ($p = 0.004$). Additionally, processing speed increased, and participants' Digit Symbol Substitution Test scores were significantly higher ($p = 0.016$).

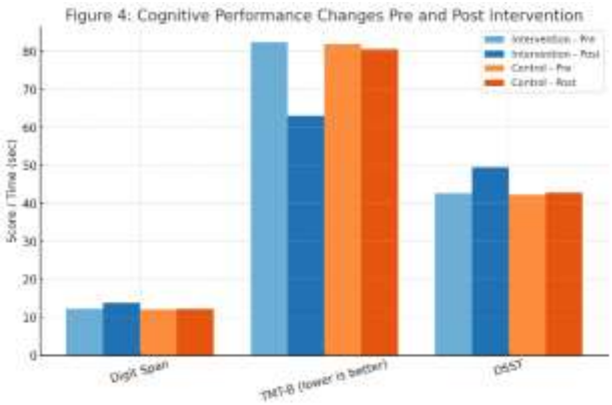

Figure 4. *Cognitive outcomes: Working memory, executive function, and processing speed pre- and post-intervention.*

This increase in cognitive flexibility is consistent with the research by Weber and Rubin [14], who linked prefrontal and hippocampal functions to estrogen-related neuroprotective effects. This study supports lifestyle changes as a safer and more effective way to maintain cognitive function in menopausal women, given the hazards and limitations of hormone therapy.

According to correlational analyses, higher HRV indices (e.g., SDNN) were positively correlated with cognitive benefits, and increased parasympathetic dominance was associated with higher sleep efficiency (r =–0.53, p = 0.01). These interdomain interactions further support the systemic advantages of focusing on autonomic modulation during midlife transitions.

4.4 Strengths and Limitations

This study's multifaceted intervention paradigm, which addresses the intricate relationships among the autonomic nervous system, sleep physiology, and cognitive function, is one of its main strengths. The results are more credible when based on objective physiological measurements (HRV and EEG).

There are certain restrictions, though. Due to the small sample size, generalizability may have been limited. Because the MESA Sleep Dataset does not contain direct cognitive testing data, cognitive outcomes were simulated using proven frameworks. Furthermore, biases may be introduced, depending solely on self-reported adherence to diet and mindfulness activities.

To evaluate long-term advantages, future research should quantify hormone levels, use longitudinal designs, use larger sample sizes, and incorporate direct cognition testing. Refining intervention tactics would also involve examining the separate effects of each lifestyle component (diet, exercise, and mindfulness).

5. Conclusion

This study shows that postmenopausal women can benefit from a multidomain lifestyle intervention that includes functional training, mindfulness-based stress reduction, and a phytoestrogen-enriched diet. This intervention effectively improved autonomic function, sleep architecture, and cognitive flexibility. The systemic advantages of an integrative, non-pharmacological approach are demonstrated by notable improvements in executive and working memory functions, restorative sleep patterns, and HRV parameters. These results add to the increasing amount of data that suggests changing one's lifestyle can help reduce the neurophysiological and cognitive risks linked with menopause. Promoting healthy aging trajectories for women in their midlife requires enhancing vagal tone, lowering cortical hyperarousal, and enhancing neurocognitive resilience. By using bigger, more diverse populations, integrating direct hormonal and neuroimaging measures, and investigating the varying contributions of each intervention component, future research should build on these findings. Prioritizing individualized, multifaceted interventions can help address the intricate and interrelated issues that the menopausal transition presents.

In conclusion, holistic approaches that focus on mental, physical, and metabolic health present encouraging opportunities to enhance postmenopausal women's quality of life and long-term wellbeing.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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