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# Post-Exercise Auricular Vagus Nerve Stimulation Modulates Autonomic and Recovery Responses in Physically Inactive Young Adults: A Randomized Controlled Trial

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**Abstract**

**Background:**
Efficient post-exercise recovery largely depends on rapid parasympathetic reactivation of the autonomic nervous system. Auricular transcutaneous vagus nerve stimulation (taVNS) has emerged as a non-invasive neuromodulatory approach with the potential to facilitate autonomic recovery following physical exertion.

**Objective:**
This study aimed to investigate the acute effects of auricular transcutaneous vagus nerve stimulation applied immediately after exercise on autonomic nervous system activity and recovery-related physiological, metabolic, and perceptual parameters in healthy young adults.

**Methods:**
This cross-sectional study with an acute intervention bout included sixty physically inactive healthy young adults (18–35 years) who were randomly allocated to an exercise + taVNS group (n = 30) or an exercise-only control group (n = 30). All participants completed a standardized 30-minute treadmill walking protocol. Immediately after exercise, the intervention group received 20 minutes of bilateral taVNS, while the control group underwent a matched recovery period. Autonomic function was assessed using heart rate variability indices, including the root mean square of successive differences (RMSSD), a time-domain indicator of parasympathetic activity, and the low-frequency/high-frequency (LF/HF) ratio, which reflects sympathovagal balance, together with cardiovascular, metabolic, and perceptual recovery markers.

**Results:**
Both groups demonstrated recovery-related improvements following exercise. However, the taVNS group showed greater reductions in systolic and diastolic blood pressure compared with the control group ($p = .003$ and $p = .004$). The parasympathetic nervous system index increased significantly more in the taVNS group ($p = .009$). Blood lactate concentration decreased more markedly in the taVNS group ($-4.90 \pm 3.02$ mmol·L$^{-1}$) than in the control group ($-1.38 \pm 0.97$

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mmol·L⁻¹; $p < .001$). Participants receiving taVNS also demonstrated a greater reduction in perceived fatigue scores ($p < .001$). In contrast, heart rate variability parameters such as heart rate, RMSSD, and LF/HF ratio showed comparable recovery patterns between groups ($p > .05$).

**Conclusion:**
Auricular transcutaneous vagus nerve stimulation applied immediately after exercise appears to enhance parasympathetic reactivation and improve cardiovascular, metabolic, and perceptual recovery beyond spontaneous post-exercise recovery. These findings suggest that taVNS may represent a feasible non-invasive strategy to support acute post-exercise recovery in healthy young adults when applied under appropriate stimulation parameters (ClinicalTrials.gov: NCT07371676).

**Keywords:** Auricular transcutaneous vagus nerve stimulation, Autonomic nervous system, Heart rate variability, Post-exercise recovery, Parasympathetic reactivation

## Introduction

The autonomic nervous system plays a pivotal role in regulating physiological homeostasis during and after exercise, with parasympathetic reactivation representing a key determinant of post-exercise recovery. The vagus nerve (Nervus vagus), as the primary peripheral conduit of parasympathetic signaling, is critically involved in cardiovascular control, respiratory regulation, immune modulation, and energy metabolism. Structurally dominated by afferent fibers, the vagus nerve transmits visceral sensory information to brainstem nuclei, thereby shaping autonomic balance and physiological stress responses [1,2].

Following intense physical activity, sympathetic activation predominates, resulting in elevated heart rate, blood pressure, and metabolic stress markers. Efficient recovery depends largely on the timely reactivation of parasympathetic pathways, whereas delayed vagal re-engagement has been associated with prolonged physiological strain and impaired recovery capacity. In this context, heart rate variability (HRV) has emerged as a widely accepted non-invasive biomarker of cardiac vagal tone and autonomic recovery dynamics in both healthy participants and athletic populations [3].

Vagus nerve stimulation (VNS) represents a neuromodulatory approach capable of influencing central and peripheral autonomic circuits through

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vagal afferent and efferent pathways. Originally developed for the treatment of refractory epilepsy and depression, VNS has evolved with the advent of non-invasive techniques, including transcutaneous and auricular vagus nerve stimulation (taVNS), enabling autonomic modulation without surgical implantation [4-7]. Neuroimaging and physiological studies have demonstrated that VNS induces functional changes in key autonomic control centers such as the brainstem, thalamus, limbic system, and hypothalamus, thereby supporting heart rate regulation, stress attenuation, and inflammatory reflex modulation—processes that are highly relevant to post-exercise recovery [8].

Accumulating evidence suggests that taVNS can acutely enhance vagal tone, improve heart rate variability (HRV) indices, and shift autonomic balance toward parasympathetic dominance. Experimental studies conducted under resting conditions have demonstrated increases in vagally mediated HRV parameters following taVNS application [9,10]. In addition, emerging exercise-related studies have reported that taVNS applied during the post-exercise period may facilitate autonomic recovery and modulate cardiorespiratory responses after aerobic exercise [11,12]. Importantly, compared with invasive cervical VNS, auricular stimulation substantially reduces the risk of adverse cardiac effects while preserving physiologically distributed bilateral vagal signaling. Recent systematic reviews and meta-analyses indicate that taVNS is generally well tolerated when applied within recommended stimulation parameters, with most reported side effects being mild and transient [10,13].

Within exercise and sports contexts, emerging studies indicate that taVNS applied after aerobic or endurance-based exercise may reduce perceived pain and fatigue, improve respiratory parameters, and promote favorable autonomic adjustments during the acute recovery phase [11,12]. Moreover, randomized controlled trials have demonstrated that non-invasive vagus nerve stimulation can enhance maximal oxygen uptake ($VO_2$peak), improve exercise capacity, and attenuate exercise-induced inflammatory responses, underscoring the physiological relevance of vagal modulation in post-exercise adaptation [14]. Beyond peripheral recovery mechanisms, vagal modulation has also been associated with reduced stress and competitive anxiety and improved autonomic resilience in elite

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athletes, suggesting an integrative influence on both physiological and psychophysiological recovery processes [15].

Despite growing interest in non-invasive vagal neuromodulation, evidence regarding the acute effects of taVNS applied immediately after exercise on autonomic nervous system regulation and recovery in healthy young adults remains limited. In particular, the extent to which taVNS can accelerate parasympathetic reactivation and optimize short-term recovery responses has yet to be fully elucidated.

Although several studies have investigated the effects of taVNS in exercise contexts, the available evidence remains limited in several important respects. Most previous studies have primarily focused on isolated physiological parameters or subjective recovery outcomes rather than providing a comprehensive assessment of post-exercise recovery processes. For instance, Hatik et al. mainly examined cycling-related recovery outcomes such as pain, fatigue, and selected physiological responses, while Güçlüer et al. focused primarily on cardiorespiratory responses and autonomic indices following aerobic exercise. Consequently, evidence regarding the immediate post-exercise application of taVNS and its influence on integrated recovery responses remains scarce. In contrast, the present randomized controlled study was designed to provide a multidimensional evaluation of acute post-exercise recovery by simultaneously assessing cardiovascular responses, heart rate variability–derived autonomic indices, metabolic recovery reflected by blood lactate clearance, and perceived fatigue in healthy young adults. Accordingly, the specific contribution of the present study lies in its integrated assessment of autonomic, metabolic, cardiovascular, and perceptual recovery responses following post-exercise taVNS.

Therefore, the aim of the present study was to investigate the acute effects of auricular transcutaneous vagus nerve stimulation applied after exercise on autonomic nervous system activity and recovery parameters in healthy young adults. We hypothesized that post-exercise taVNS would facilitate

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parasympathetic reactivation, improve autonomic balance, and enhance acute recovery responses compared with control conditions.

## Materials and Methods

### Study Design

This study was designed as a randomized, controlled, single-session experimental trial to investigate the acute effects of post-exercise taVNS on autonomic nervous system activity and recovery-related parameters in healthy young adults.

All procedures were conducted in accordance with the principles of the Declaration of Helsinki. Ethical approval for the study was obtained from the Istanbul Gelişim University Ethics Committee (Meeting No: 2024/05, Decision No: 2024-05-88, approval date: 19 April 2024), which confirmed that the study protocol complied with relevant ethical standards. Written informed consent was obtained from all participants prior to enrollment. The study was prospectively registered as a clinical trial at ClinicalTrials.gov (Registration No: NCT07371676, registration date: 28 January 2026).

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### Participants

A total of 60 healthy young adults aged between 18 and 35 years were recruited on a voluntary basis. Physical activity levels were assessed using the International Physical Activity Questionnaire (IPAQ). Only individuals classified as Category 1 (Inactive) according to the IPAQ scoring protocol were included in the study to ensure that the sample consisted exclusively of physically inactive participants (Figure 1).

Eligible participants were healthy young adults aged between 18 and 35 years who had no regular exercise habits, were classified as physically inactive according to the International Physical Activity Questionnaire (IPAQ), and voluntarily agreed to participate by providing written informed consent. Participants were excluded if they engaged in regular physical training or athletic activity; had a history or current diagnosis of cardiovascular, respiratory, neurological, psychiatric, or metabolic

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disorders; used medications known to affect autonomic or cardiovascular function; had a history of cardiac or respiratory disease; presented with an acute or chronic musculoskeletal injury; had an active ear infection, open wound, or dermatological condition affecting the auricle; or were pregnant or suspected to be pregnant. Participants who requested withdrawal or developed exclusion criteria during the protocol were removed from the study.

Independent samples t-tests were conducted to compare baseline demographic and anthropometric variables between the control and taVNS groups (Table 1). Prior to analysis, the assumption of homogeneity of variances was verified using Levene's test, which indicated equal variances for all variables ($p > .05$); therefore, t-test results assuming equal variances were reported. As presented in Table 1, the analyses revealed no statistically significant between-group differences in age ($t(56) = 1.435$, $p = .157$, Cohen's $d = -0.38$), height ($t(56) = 0.305$, $p = .762$, Cohen's $d = -0.08$), or body mass ($t(56) = -0.567$, $p = .573$, Cohen's $d = 0.15$). Effect size estimates indicated negligible differences for height and body mass and a small-to-moderate difference for age; however, none were considered sufficient to compromise group equivalence. These findings confirm that the groups were highly comparable in terms of baseline demographic and anthropometric characteristics, allowing subsequent outcome differences to be attributed to the experimental intervention rather than participant-related factors.

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**Figure 1.** CONSORT 2025 Flow Diagram

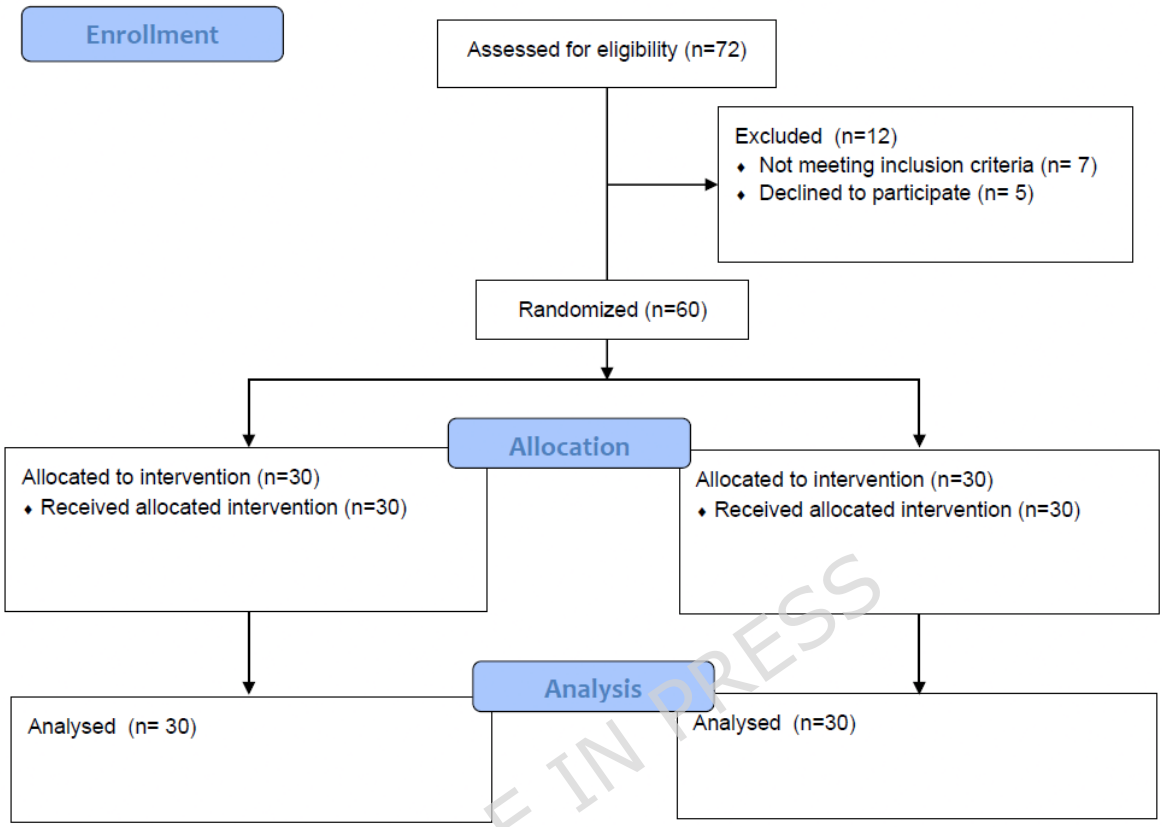



**Table 1.** Baseline characteristics of participants

| Variable | Control Group (n = 30) Mean ± SD | taVNS Group (n = 30) Mean ± SD | p value |
|---|---|---|---|
| **Age (years)** | 21.38 ± 1.70 | 20.79 ± 1.40 | .157 |
| **Height (cm)** | 170.97 ± 7.84 | 170.34 ± 7.66 | .762 |
| **Body Mass (kg)** | 65.79 ± 10.51 | 67.48 ± 12.13 | .573 |
| **Sex (Male/Female)** | 15 / 15 | 15 / 15 | — |

Participant characteristics, including age, height, body mass and sex distribution, are presented in Table 1. The analysis revealed no statistically significant differences between groups for baseline demographic and anthropometric characteristics, indicating that the groups were comparable prior to the intervention. In addition, the sex distribution was balanced between groups, with equal representation of male and female participants in both the control and taVNS groups.

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Prior to parametric analyses, data normality was assessed using the Shapiro–Wilk test because the sample size for each group was below 50. Variables with $p > .05$ were considered normally distributed, whereas values of $p < .05$ indicated deviations from normality. This procedure ensured the appropriate selection of subsequent statistical tests.

**Randomization and Group Allocation**

Following baseline assessments, participants were randomly allocated into two groups using a computer-generated randomization procedure:

1. **Exercise + taVNS Group (n = 30)**
2. **Exercise + Control Group (n = 30)**

In the control group participants were allowed to rest for 20 minutes after the walk without any intervention.

**Randomization, Allocation Concealment and Blinding**

Participants were randomly assigned to either the exercise + taVNS group or the exercise-only control group using a computer-generated randomization sequence created with the Randomization software available at Randomize.org. A simple 1:1 allocation ratio was applied.

The random allocation sequence was generated by an independent researcher who was not involved in participant recruitment, assessment procedures, intervention delivery, or data analysis. After eligibility screening and baseline measurements, each participant was assigned a study identification number and allocated according to the pre-generated randomization list.

To ensure allocation concealment, the group assignments were placed in sequentially numbered, opaque, sealed envelopes prepared by the same independent researcher. The envelopes were opened only after completion of baseline measurements and immediately before the intervention session. The investigator responsible for outcome assessments did not have access to the randomization sequence.

The personnel responsible for enrolling participants were different from those assigning participants to interventions. Group allocation was therefore concealed until the moment of assignment.

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This study was conducted using a double-blind design. Participants were unaware of their group allocation, and the outcome assessor and data analyst were also blinded to group assignment during data collection and statistical analysis. Participants were unaware of their group allocation and were informed that two different recovery procedures were being compared. In the intervention group, auricular transcutaneous vagus nerve stimulation was applied, whereas the control group underwent a sham procedure consisting of passive seated rest with identical preparation procedures and electrode placement explanation to minimize expectancy bias. Outcome assessors and data analysts were also blinded to group allocation during data collection and statistical analysis.

In the control condition, participants remained seated and rested quietly for 20 minutes following the exercise protocol. This approach was selected to isolate the physiological recovery process without additional neuromodulatory stimulation. Participants were informed that two different post-exercise recovery procedures were being compared, which helped reduce expectancy effects regarding the intervention.

**Exercise Protocol**

All participants completed a single-session treadmill walking protocol consisting of 30 minutes of continuous walking at a fixed speed of 6 $km \cdot h^{-1}$ on a motorized treadmill under standardized laboratory conditions. The treadmill speed was kept constant for all participants and was not individually adjusted during the exercise session in order to ensure a comparable exercise stimulus between participants and study groups. This walking speed corresponds to a low-to-moderate intensity level for healthy young adults and was selected to induce physiological activation while remaining tolerable for physically inactive participants. Participants were instructed to walk continuously for the entire duration of the protocol without altering the treadmill settings. Total walking distance was recorded for descriptive purposes.

**Auricular Transcutaneous Vagus Nerve Stimulation**

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Immediately following the exercise protocol, participants received either active taVNS. Active taVNS was applied bilaterally to vagally innervated auricular regions using a Vagustim device (Vagustim, Istanbul, Türkiye) via auricular electrodes, with stimulation parameters set at a frequency of 10 Hz, a biphasic waveform, a pulse width of 300 μs, and delivered in modulation mode for a total duration of 20 minutes; stimulation intensity was individually adjusted to the highest comfortable sensory threshold without eliciting pain. In the control group participants were allowed to rest for 20 minutes after the walk without any intervention [16].

In the control group, participants underwent an equivalent 20-minute recovery period in a seated resting position without electrical stimulation. The duration and environmental conditions were matched to the intervention group to ensure comparable post-exercise recovery conditions.

During both the stimulation and control recovery periods, participants remained seated in a comfortable upright position to ensure standardized measurement conditions and minimize movement-related variability in autonomic recordings.

In addition to standard HRV parameters, the stress index was obtained from the Elite HRV software. The stress index is a derived HRV parameter calculated from heart rate variability patterns and reflects the balance between sympathetic and parasympathetic autonomic activity. Higher values indicate greater sympathetic activation, whereas lower values reflect a shift toward parasympathetic dominance during recovery.

**Outcome Measures**

The primary outcome of this randomized controlled trial was the change in cardiac autonomic recovery following exercise, assessed using heart rate variability (HRV) parameters. The principal HRV variable was the root mean square of successive differences (RMSSD), which represents the square root of the mean of the squared differences between adjacent normal R–R intervals. RMSSD is widely accepted as a time-domain indicator of parasympathetic (vagal) activity, and higher RMSSD values

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during recovery reflect faster parasympathetic reactivation following exercise.

Additional HRV-derived parameters included the R–R interval and the low-frequency to high-frequency ratio (LF/HF). The R–R interval represents the time between consecutive heartbeats, and longer R–R intervals during recovery indicate reduced heart rate and increased parasympathetic influence. For frequency-domain HRV analysis, the low-frequency (LF) component was defined as spectral power averaged within the 0.04–0.15 Hz range, whereas the high-frequency (HF) component was defined as spectral power averaged within the 0.15–0.40 Hz range. The LF/HF ratio reflects sympathovagal balance, where lower values generally indicate a shift toward parasympathetic dominance during recovery.

Autonomic indices also included the sympathetic nervous system (SNS) index and parasympathetic nervous system (PNS) index derived from HRV-based analysis using Elite HRV software. These indices provide composite measures of autonomic balance calculated from time- and frequency-domain HRV parameters. Decreases in the SNS index and increases in the PNS index during recovery indicate enhanced parasympathetic reactivation and reduced sympathetic dominance following exercise.

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Secondary outcomes included post-exercise physiological and perceptual recovery indicators such as heart rate, systolic and diastolic blood pressure, respiratory rate, blood lactate concentration, and perceived fatigue scores. Improved recovery was characterized by reductions in heart rate, blood pressure, respiratory rate, blood lactate levels, and perceived fatigue during the recovery period following exercise.

**Autonomic Nervous System Activity**

Autonomic function was assessed using heart rate variability (HRV) measurements recorded with a Polar H10 chest strap. Data were transmitted via Bluetooth to a mobile device and analyzed using Elite HRV software. Measurements were performed in a seated position during a 1-minute resting period, ensuring minimal movement and verbal interaction.

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### Heart Rate and Blood Pressure

Heart rate, systolic blood pressure, and diastolic blood pressure were measured from the right wrist using a Visomat digital sphygmomanometer under standardized conditions.

### Fatigue Assessment

Perceived fatigue was assessed using a Numeric Fatigue Rating Scale (0–10), where higher scores indicated greater fatigue.

### Blood Lactate Concentration

Blood lactate levels were measured using a Lactate Scout Plus device. Capillary blood samples were obtained from the middle finger of the right hand to avoid interference with auricular stimulation. The sampling site was cleaned and sterilized prior to measurement.

### Outcomes

The primary outcome of this randomized controlled trial was the change in cardiac autonomic recovery following exercise, quantified by HRV parameters. The principal HRV variable was the RMSSD, which reflects parasympathetic reactivation after exercise.

Secondary outcomes included additional HRV indices (RR interval, LF/HF ratio), heart rate recovery response, and post-exercise physiological recovery indicators measured immediately after the intervention period.

All outcomes were assessed under standardized laboratory conditions at baseline and immediately following completion of the recovery intervention.

### Statistical Analysis

Statistical analyses were conducted using IBM SPSS Statistics (Version 26, IBM Corp., Armonk, NY, USA). Descriptive data are presented as mean ± standard deviation (SD) for normally distributed variables and as median (minimum–maximum) for non-normally distributed variables. Data normality was assessed using the Shapiro–Wilk test, given that the sample

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size in each group was below 50, and homogeneity of variances was examined with Levene's test. Baseline demographic and anthropometric characteristics were compared between groups using independent samples t-tests, while the association between group allocation and sex distribution was evaluated using the Chi-square test of independence ($\chi^2$). Within-group pre–post comparisons were performed using paired samples t-tests for normally distributed variables and Wilcoxon signed-rank tests for non-normally distributed variables. Between-group comparisons of change scores ($\Delta$ = post − pre) were conducted using the Mann–Whitney U test. Effect sizes were calculated using Cohen's d and interpreted as small (0.2), moderate (0.5), or large (0.8). All statistical tests were two-tailed, and statistical significance was set at $p < .05$.

Change scores ($\Delta$ values) were calculated for each participant as the difference between post-intervention and pre-intervention measurements ($\Delta$ = post − pre). The group-level mean change scores were additionally verified against the corresponding pre- and post-intervention group means to ensure internal consistency of the reported tables. Between-group comparisons were performed using these individual change scores rather than the subtraction of group-level means. Therefore, the values presented in Table 3 represent the mean and standard deviation of individual participant change scores.

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**Results**

Within-group analyses revealed significant pre- to post-intervention changes in all physiological, autonomic, and perceptual parameters following auricular transcutaneous vagus nerve stimulation. Heart rate and systolic blood pressure demonstrated significant reductions after the intervention (both $p < .001$), accompanied by a marked decrease in diastolic blood pressure ($t = -12.35$, $p < .001$). Autonomic indices showed a pronounced shift toward parasympathetic dominance, as evidenced by a significant increase in R–R interval (RR) interval and Root Mean Square of Successive Differences (RMSSD) values, alongside a reduction in sympathetic nervous system (SNS) index and Low Frequency / High

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Frequency ratio (LF/HF) ratio (all $p < .001$). Conversely, the parasympathetic nervous system (PNS) index increased significantly following stimulation ($p < .001$).

Respiratory rate also decreased significantly after taVNS ($t = -8.72$, $p < .001$), indicating improved respiratory recovery. In parallel, blood lactate concentration exhibited a substantial reduction from pre- to post-intervention levels ($t = -8.73$, $p < .001$), reflecting enhanced metabolic recovery. Perceived stress and fatigue scores were significantly lower following stimulation (both $p < .001$). Collectively, these findings indicate that post-exercise taVNS elicited robust acute improvements in cardiovascular regulation, autonomic balance, metabolic clearance, and subjective recovery markers in healthy young adults.

Within-group analyses indicated significant recovery-related changes in both the taVNS and control groups following exercise (Table 2). In both groups, heart rate, systolic and diastolic blood pressure, respiratory rate, blood lactate concentration, and perceived fatigue scores decreased from pre- to post-exercise measurements. In parallel, RR interval, RMSSD, and PNS index increased during the recovery period, while SNS index and LF/HF ratio decreased, reflecting a shift toward parasympathetic dominance following exercise. These changes were observed in both groups and represent the expected physiological recovery response after physical exertion.

**Table 2.** Pre- and post-exercise comparisons of physiological and autonomic parameters in the taVNS and control groups

| Parameter | taVNS Pre Mean ± SD | taVNS Post Mean ± SD | Control Pre Mean ± SD | Control Post Mean ± SD |
|---|---|---|---|---|
| **Heart rate (bpm)** | 88.52 ± 7.49 | 79.83 ± 7.56 | 89.86 ± 7.76 | 81.41 ± 7.08 |
| **Systolic BP (mmHg)** | 129.31 ± 8.18 | 116.41 ± 9.75 | 129.55 ± 5.36 | 120.34 ± 5.55 |

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| | | | | |
|---|---|---|---|---|
| **Diastolic BP (mmHg)** | 85.93 ± 10.74 | 73.59 ± 8.65 | 89.45 ± 7.65 | 81.00 ± 7.16 |
| **RR interval (ms)** | 709.48 ± 80.60 | 763.28 ± 77.97 | 614.34 ± 102.56 | 669.52 ± 107.16 |
| **RMSSD (ms)** | 36.76 ± 21.31 | 54.31 ± 24.94 | 24.79 ± 11.02 | 39.17 ± 19.54 |
| **SNS index** | 1.82 ± 1.14 | 0.93 ± 0.96 | 4.12 ± 2.40 | 3.08 ± 2.12 |
| **PNS index** | -1.05 ± 0.98 | -0.21 ± 1.21 | -1.33 ± 0.94 | -0.87 ± 1.00 |
| **Respiratory rate (breaths·min⁻¹)** | 16.99 ± 3.33 | 12.95 ± 4.14 | 16.87 ± 4.34 | 13.81 ± 3.79 |
| **Stress index** | 12.62 ± 3.55 | 9.74 ± 3.42 | 14.52 ± 6.84 | 11.63 ± 4.66 |
| **LF/HF ratio** | 3.13 ± 1.90 | 1.24 ± 1.05 | 4.38 ± 1.59 | 3.21 ± 1.44 |
| **Blood lactate (mmol·L⁻¹)** | 8.72 ± 4.16 | 3.82 ± 1.86 | 6.32 ± 2.24 | 4.94 ± 2.21 |
| **Perceived fatigue score** | 6.17 ± 1.14 | 3.69 ± 1.31 | 4.76 ± 1.18 | 3.21 ± 1.32 |

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Baseline comparisons indicated no significant differences between the taVNS and control groups for any of the outcome variables prior to the intervention (all $p > .05$), confirming that the groups were comparable at baseline.

Between-group analyses revealed significant differences favoring the taVNS group for several recovery-related outcomes (Table 3). Reductions in systolic and diastolic blood pressure were significantly greater in the taVNS group compared with the control group ($p = .003$ and $p = .004$,

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respectively), with large effect sizes (Cohen's d ≈ −0.80), indicating enhanced cardiovascular recovery following vagal stimulation.

Change scores (Δ values) were calculated for each participant as the difference between post-intervention and pre-intervention measurements (Δ = post − pre). Between-group comparisons were performed using these individual change scores rather than the subtraction of group-level means. Therefore, the values presented in Table 3 represent the mean and standard deviation of individual participant change scores.

Indices of autonomic regulation further demonstrated group-specific effects. The increase in parasympathetic nervous system (PNS) index was significantly greater in the taVNS group than in the control group ($p = .009$), with a moderate-to-large effect size ($d = 0.61$), suggesting a more pronounced parasympathetic reactivation with stimulation. In contrast, changes in heart rate, RR interval, RMSSD, SNS index, respiratory rate, stress index, and LF/HF ratio did not differ significantly between groups ($p > .05$), indicating comparable trends for these parameters across conditions.

Metabolic and perceptual recovery outcomes showed the most robust between-group differences. The reduction in blood lactate concentration was significantly greater in the taVNS group compared with the control group ($p < .001$), with a very large effect size ($d = −1.57$). Similarly, perceived fatigue decreased more markedly in the taVNS group ($p < .001$), also demonstrating a large effect ($d = −1.26$). These findings indicate that post-exercise taVNS produced substantially greater improvements in metabolic clearance and subjective recovery than exercise alone (Table 3).

**Table 3.** Between-group comparisons of individual change scores (Δ = post − pre) in physiological and autonomic parameters

| Parameter | taVNS Group (n = 30) | Control Group (n = | Test statistic | p value | Cohen's d |
|---|---|---|---|---|---|

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| | Mean ± SD | 30) Mean ± SD | | | |
|---|---|---|---|---|---|
| **Heart rate (bpm)** | −8.69 ± 4.29 | −8.45 ± 5.30 | U = 380.0 | .533 | −0.05 |
| **Systolic BP (mmHg)** | −12.89 ± 5.03 | −9.21 ± 3.97 | U = 228.0 | **< .003** | −0.81 |
| **Diastolic BP (mmHg)** | −12.35 ± 4.36 | −8.45 ± 5.37 | U = 237.5 | **< .004** | −0.80 |
| **RR interval (ms)** | 53.79 ± 30.12 | 55.17 ± 33.77 | U = 433.5 | .846 | −0.04 |
| **RMSSD (ms)** | 17.55 ± 11.60 | 14.38 ± 11.72 | U = 518.0 | .131 | 0.27 |
| **SNS index** | -0.89 ± 0.67 | −1.05 ± 1.07 | U = 392.0 | .612 | 0.12 |
| **PNS index** | 0.84 ± 0.68 | 0.46 ± 0.56 | U = 589.5 | **< .009** | 0.61 |
| **Respiratory rate (breaths·min⁻¹)** | -4.04 ± 3.45 | −3.07 ± 2.05 | U = 368.0 | .410 | −0.42 |
| **Stress index** | -2.88 ± 2.06 | −2.89 ± 4.15 | U = 336.5 | .194 | 0.01 |
| **LF/HF ratio** | −1.89 ± 1.56 | −1.17 ± 0.93 | U = 322.0 | .128 | −0.56 |
| **Blood lactate (mmol·L⁻¹)** | −4.90 ± 3.02 | −1.38 ± 0.97 | U = 116.5 | **< .001** | −1.57 |
| **Perceived fatigue score** | −2.48 ± 0.74 | −1.55 ± 0.74 | U = 171.5 | **< .001** | −1.26 |

Mann–Whitney U test was used for between-group comparisons.

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## Discussion

The present study investigated the acute effects of post-exercise taVNS on autonomic nervous system regulation and recovery-related parameters in healthy young adults. The principal findings demonstrate that taVNS applied immediately after exercise facilitates parasympathetic reactivation and improves autonomic balance during the early recovery phase. The findings of the present study suggest that taVNS applied immediately after

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exercise may contribute to improvements in autonomic balance during the early recovery phase, as reflected by changes in the PNS index.

Importantly, between-group comparisons were performed using participant-level change scores rather than differences of group means, which provides a more appropriate statistical approach for paired experimental data.

The present study contributes to the growing literature on non-invasive vagal neuromodulation in exercise recovery by simultaneously examining cardiovascular, autonomic, metabolic, and perceptual recovery markers within a randomized controlled experimental design. While previous studies have primarily focused on single outcomes such as fatigue perception or cardiorespiratory parameters, the current findings provide a more integrated perspective on post-exercise recovery processes by demonstrating concurrent improvements in blood pressure regulation, parasympathetic reactivation, metabolic clearance (blood lactate), and perceived fatigue. This multidimensional assessment offers new insight into the potential role of taVNS as a recovery-enhancing neuromodulatory intervention.

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Although transcutaneous auricular vagus nerve stimulation is generally considered well tolerated when applied with appropriate stimulation parameters, careful monitoring of stimulation intensity and individual responses remains important in both research and clinical applications.

Acute, and particularly exhaustive, exercise is well known to induce a pronounced withdrawal of parasympathetic activity alongside sympathetic dominance, leading to marked reductions in heart rate variability (HRV) indices such as RMSSD and pNN50 [17,18]. Delayed parasympathetic reactivation following exercise has been associated with increased physiological strain, impaired recovery capacity, and reduced readiness for subsequent physical demands [19]. Within this framework, the improvements observed in autonomic indices following taVNS suggest that vagal stimulation may actively counteract exercise-induced autonomic imbalance and promote a more efficient recovery process.

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The present findings are consistent with prior experimental evidence demonstrating that auricular vagus nerve stimulation reduces exercise-related fatigue and pain while enhancing recovery in healthy participants. In randomized trials, bilateral taVNS has been shown to attenuate perceived fatigue following cycling exercise, supporting the notion that vagal afferent stimulation can modulate both physiological and perceptual components of post-exercise recovery [12]. The current study extends this literature by providing further evidence that taVNS not only influences subjective outcomes but also enhances objective markers of autonomic recovery.

From a broader recovery perspective, parasympathetic reactivation is widely regarded as a central mechanism underlying effective post-exercise restoration of homeostasis. Systematic evidence indicates that recovery strategies capable of increasing vagally mediated HRV—particularly RMSSD—are associated with improved recovery quality, cardiovascular protection, and enhanced training readiness [20]. In this context, the autonomic improvements observed following taVNS suggest that this intervention may function as an active neuromodulatory recovery strategy rather than a purely passive modality.

Recent high-impact evidence further reinforces the physiological relevance of non-invasive vagal stimulation in exercise contexts. Ackland et al. (2025) demonstrated that repeated transcutaneous vagus nerve stimulation significantly improved $VO_2$peak and attenuated inflammatory responses in healthy volunteers [14]. Although their study focused on longer stimulation periods and exercise capacity outcomes, the present findings indicate that even a single, acute application of taVNS following exercise can elicit meaningful autonomic effects. This highlights the sensitivity of the autonomic nervous system to vagal neuromodulation, even within short recovery windows.

Beyond cardiovascular regulation, vagal afferent activation has been shown to influence central mechanisms involved in affective and interoceptive processing. Experimental studies indicate that taVNS

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enhances mood recovery following both physical and cognitive effort, likely via modulation of brainstem–limbic circuits implicated in stress regulation and interoception [21]. Although psychological outcomes were not directly assessed in the present study, improved autonomic recovery may indirectly contribute to enhanced subjective recovery, reduced perceived exertion, and improved well-being after exercise.

Mechanistic support for these findings is provided by studies demonstrating that vagus nerve stimulation induces mild reductions in heart rate alongside alterations in respiratory patterns, including increased breathing frequency and reduced tidal volume, reflecting enhanced vagal efferent influence on cardiopulmonary control [22]. Although these effects were primarily described in patients with implanted VNS devices, they offer important insight into how vagal modulation may influence exercise physiology and recovery processes.

Additional exercise-based research indicates that auricular transcutaneous vagus nerve stimulation can accelerate parasympathetic reactivation following aerobic exercise. In healthy participants, taVNS has been reported to influence certain cardiorespiratory responses following aerobic exercise, including pulmonary function parameters such as forced expiratory volume ($FEV_1$), although changes in autonomic indices such as RMSSD and SNS/PNS indices were not significantly different between groups in that study [13]. These findings align with the present results, suggesting that taVNS may facilitate a more rapid restoration of autonomic homeostasis after physical exertion, even when traditional HRV metrics demonstrate variable short-term sensitivity.

Beyond healthy populations, clinical evidence highlights the potential relevance of taVNS in participants with impaired recovery capacity. In patients with post-COVID syndrome, taVNS applied after aerobic exercise increased parasympathetic nervous system activity and cardiac vagal control compared with placebo stimulation, underscoring its therapeutic potential in conditions characterized by autonomic dysregulation and exercise intolerance [23]. These observations suggest that vagal

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neuromodulation may be particularly beneficial in populations with reduced autonomic flexibility, a concept that may also extend to overtrained athletes or participants exposed to chronic physiological stress.

From a broader physiological standpoint, exercise-induced autonomic imbalance is closely linked to inflammatory and oxidative stress pathways. Comprehensive reviews emphasize that excessive or high-intensity exercise can transiently suppress parasympathetic activity while enhancing sympathetic drive, thereby promoting oxidative stress and low-grade inflammation [24]. In this context, interventions that enhance vagal activity—such as taVNS—may exert indirect anti-inflammatory and antioxidative effects by restoring autonomic balance, providing a plausible biological mechanism for the recovery-enhancing effects observed following vagal stimulation.

In sports science, auricular VNS has recently been proposed as a novel, non-doping recovery strategy capable of improving autonomic regulation, reducing fatigue, and potentially lowering injury risk associated with insufficient recovery [25]. The ability of taVNS to selectively stimulate afferent vagal pathways via the nucleus tractus solitarius suggests that its effects extend beyond peripheral cardiovascular control to include central autonomic and interoceptive processing. This central–peripheral integration may explain why improvements in recovery can occur even in the absence of large immediate changes in traditional HRV indices.

Despite these strengths, several limitations should be acknowledged. The study sample consisted of physically inactive healthy young adults, which may limit the generalizability of the findings to trained athletes or clinical populations. Moreover, only acute responses were evaluated, precluding conclusions regarding long-term adaptations to repeated post-exercise taVNS. Given that autonomic recovery dynamics are influenced by exercise intensity, duration, modality, and training status [19,26], future randomized controlled trials should investigate longitudinal effects, dose–response relationships, and sport-specific applications of taVNS.

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Several limitations should be considered when interpreting the findings of the present study. First, the sample consisted of physically inactive healthy young adults, which may limit the generalizability of the results to trained athletes, older individuals, or clinical populations with altered autonomic regulation. Second, the study evaluated only the acute responses to a single post-exercise taVNS session, and therefore the long-term or cumulative effects of repeated stimulation cannot be determined. Third, although heart rate variability indices were used to assess autonomic nervous system activity, these measures may be influenced by factors such as breathing patterns and short-term physiological fluctuations during the recovery period.

Another important limitation is that heart rate was not monitored during the treadmill walking protocol. Therefore, although the exercise speed was standardized and selected to represent a tolerable low-to-moderate workload for physically inactive young adults, the actual relative exercise intensity may have varied substantially between participants depending on individual fitness level and cardiovascular responsiveness. As a result, some participants may have performed the protocol at a light relative intensity, whereas others may have reached moderate or even higher cardiovascular intensity ranges. This limitation is particularly relevant because the present study primarily reports cardiovascular and autonomic recovery outcomes. Future studies should include continuous heart rate monitoring during exercise to better characterize individual exercise intensity and improve interpretation of post-exercise recovery responses.

Another limitation relates to the control condition used in the present study. Although the control group followed the same exercise protocol and recovery duration, a passive seated rest condition was used rather than a sham stimulation procedure. In several taVNS studies, earlobe stimulation has been employed as a sham condition to mimic the sensory feedback associated with active stimulation and to improve participant blinding. In the current design, the absence of electrical stimulation in the control group may have limited complete participant blinding and may have

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introduced potential expectancy effects, particularly for subjective outcomes such as perceived fatigue.

Additionally, although the reductions in blood pressure observed during recovery may reflect normal post-exercise physiological responses, pronounced decreases could theoretically increase the risk of orthostatic hypotension upon standing, particularly in susceptible or clinical populations. Future studies should therefore examine cardiovascular responses to post-exercise taVNS in populations with impaired autonomic regulation.

Furthermore, unlike implanted vagus nerve stimulation systems, transcutaneous auricular vagus nerve stimulation provides indirect stimulation of the vagus nerve through the skin, and the exact level of neural activation cannot be directly quantified. Consequently, the magnitude of neural stimulation is generally inferred from stimulation parameters and physiological responses.

Finally, although perceived fatigue was assessed using a 0–10 rating scale in the present study, other subjective recovery indicators such as mood state, perceived recovery status, or psychological stress were not evaluated. Including a broader range of perceptual outcomes in future studies may provide a more comprehensive understanding of the effects of taVNS on post-exercise recovery.

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## Conclusion

In conclusion, the present study demonstrates that auricular transcutaneous vagus nerve stimulation applied immediately after exercise shows potential to support autonomic recovery and optimizes autonomic recovery in healthy young adults. By facilitating vagal rebound during the early recovery phase, taVNS appears to counteract exercise-induced autonomic imbalance and promote a more efficient restoration of physiological homeostasis.

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These findings contribute to the growing body of evidence supporting non-invasive vagal neuromodulation as a safe, feasible, and physiologically meaningful strategy for post-exercise recovery. Given its non-doping nature and ease of application, taVNS holds promise as an adjunctive recovery intervention in both recreational and competitive exercise settings.

Future research should focus on longitudinal effects, optimal stimulation parameters, and population-specific responses to taVNS, including trained athletes and participants with autonomic dysregulation. Integrating objective autonomic markers with subjective recovery outcomes and performance measures will be essential to fully elucidate the role of taVNS within evidence-based recovery protocols. Nevertheless, further randomized controlled trials including sham stimulation conditions are required to confirm these findings and to minimize potential expectancy effects.

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**Abbreviations**

**HRV:** Heart rate variability

**VNS:** Vagus nerve stimulation

**taVNS:** Auricular transcutaneous vagus nerve stimulation

**IPAQ:** International physical Activity Questionnaire

**SNS:** Sympathetic nervous system

**PNS:** Parasympathetic nervous system

**RR:** R–R interval

**RMSSD:** Root Mean Square of Successive Differences

**LF/HF:** Low Frequency / High Frequency ratio

**Ethics approval and consent to participate**

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All procedures were conducted in accordance with the principles of the Declaration of Helsinki. Ethical approval for the study was obtained from the Istanbul Gelisim University Ethics Committee (Meeting No: 2024/05, Decision No: 2024-05-88, approval date: 19 April 2024), which confirmed that the study protocol complied with relevant ethical standards. Written informed consent was obtained from all participants prior to enrollment. The study was prospectively registered as a clinical trial at ClinicalTrials.gov (Registration No: NCT07371676, registration date: 28 January 2026).

## Consent for publication

Not applicable.

## Availability of data and materials

The datasets generated and/or analyzed during the current study are not publicly available due to ethical restrictions related to participant confidentiality and the inclusion of sensitive clinical data. However, the data are available from the corresponding authors upon reasonable request, subject to approval by the Ethics Committee of Istanbul Gelisim University.

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## Competing interests

No.

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## Author Contributions

ÇE: Formal Analysis, Investigation, Writing – original draft, Data curation, Methodology, Supervision, Visualization RM: Writing – original draft, Writing – review and editing, Investigation, Methodology, Supervision.

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**Generative AI statement**

The author(s) declare that no Generative AI was used in the creation of this manuscript.

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