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Research Article

Influence of Pranayama and Asana Practice on Autonomic Nervous System Regulation, Heart Rate Variability, and Recovery in High-Intensity Interval Training Athletes

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Abstract

Background: High-intensity interval training (HIIT) imposes substantial autonomic and metabolic stress, potentially compromising recovery and adaptive capacity. Yoga, through pranayama (breath control) and asana (physical postures), has been proposed to enhance parasympathetic tone and accelerate recovery, yet empirical evidence from sham-controlled trials in athletic populations remains limited.

Objective: This study investigated the specific effects of a 12-week pranayama and asana intervention on autonomic nervous system regulation, heart rate variability (HRV), and recovery markers in athletes engaged in regular HIIT, relative to an attention-matched sham control.

Methods: One hundred twenty trained athletes were randomised to either a Yoga + HIIT group (n = 60) or a Sham Control + HIIT group (n = 60). A priori power analysis indicated this sample provided 80% power to detect a moderate effect (Cohen's d = 0.50) in HRV parameters at α = 0.05. The Yoga group performed 30 minutes of supervised pranayama and asana practice three times weekly immediately following HIIT sessions. The Sham group received an equivalent duration of non-yogic static stretching, neutral breathing, and supine rest, matched for attention, social interaction, and session structure. Both groups maintained equivalent HIIT training loads (monitored via session RPE and duration). Assessments at baseline, 6 weeks, and 12 weeks were conducted by assessors blinded to group allocation. Primary outcomes were time-domain HRV indices (RMSSD, SDNN, pNN50), with respiratory rate recorded and controlled as a covariate to prevent respiratory confounding. Secondary outcomes included frequency-domain HRV (interpreted cautiously), resting heart rate, heart rate recovery, salivary cortisol (collected at standardized waking times with menstrual cycle phase controlled in females), subjective recovery, sleep quality, perceived exertion, and 3000m time trial performance. The Benjamini–Hochberg false discovery rate (FDR) procedure-controlled Type I error across primary outcomes. Missing data were addressed via multiple imputation under an intent-to-treat framework. Causal mediation analysis (bootstrapped) examined whether HRV changes mediated recovery outcomes.

Results: Intent-to-treat analysis demonstrated that the Yoga + HIIT group exhibited significant improvements in primary time-domain HRV indices compared with the Sham group after FDR correction (all q < 0.001): RMSSD (+12.4 ms vs. +3.2 ms), SDNN (+15.1 ms vs. +3.8 ms), and pNN50 (+9.2% vs. +2.1%). Respiratory rate did not differ between groups at any time point (p > 0.05), and results remained significant when respiratory rate was covaried. The Yoga group also showed superior recovery markers: resting heart rate (−6.8 bpm vs. −2.1 bpm), heart rate recovery (+7.9 bpm vs. +2.8 bpm), salivary cortisol (−5.8 nmol/L vs. −1.5 nmol/L), subjective recovery (+2.1 vs. +0.6), and sleep quality (−2.9 vs. −0.6 PSQI). Performance outcomes favored the intervention group (3000m time trial: −21.4 s vs. −7.8 s; RPE: −2.5 vs. −1.2), all q < 0.001. Mediation analysis indicated that RMSSD change significantly mediated the

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effect of group assignment on heart rate recovery and cortisol reduction (bootstrapped 95% CIs excluded zero). No serious adverse events occurred; adherence was 86.3% and 84.7%, respectively.
Conclusion: Integrating pranayama and asana practice with HIIT specifically enhances autonomic regulation, accelerates recovery, and improves performance beyond non-specific attention and relaxation effects in trained athletes. Yoga should be considered a structured adjunctive recovery modality in high-performance training programs, though longer-term follow-up is required to confirm the durability of benefits.

KEYWORDS: pranayama, asana, yoga, heart rate variability, autonomic nervous system, recovery, high-intensity interval training, athletes, sham-controlled trial.

1. INTRODUCTION

High-intensity interval training (HIIT) has become a cornerstone of athletic conditioning across numerous sports, characterised by repeated bouts of maximal or near-maximal effort interspersed with brief recovery periods (Buchheit & Laursen, 2013). While HIIT elicits profound cardiorespiratory and metabolic adaptations, the substantial sympathetic activation and autonomic stress imposed by this training modality can compromise recovery, increase injury risk, and precipitate overtraining syndrome when training volumes are not adequately balanced with restorative practices (Le Meur et al., 2013). The autonomic nervous system (ANS), comprising the sympathetic and parasympathetic branches, serves as the primary regulatory interface between physiological stress and adaptive recovery. Heart rate variability (HRV), the beat-to-beat fluctuation in inter-beat intervals, has emerged as a non-invasive, reliable index of autonomic modulation, with higher time-domain HRV generally reflecting greater parasympathetic tone and enhanced cardiac adaptability (Task Force, 1996).

Yoga, an ancient mind-body practice originating in India, encompasses physical postures (asana), breath control techniques (pranayama), and meditation (dhyana). Contemporary research has documented the physiological effects of yoga on cardiovascular, respiratory, neuromuscular, and endocrine systems (Ross & Thomas, 2010). Pranayama practices, particularly slow diaphragmatic breathing and alternate nostril breathing (nadi shodhana), have been shown to stimulate the vagus nerve, increase parasympathetic tone, and improve baroreflex sensitivity (Pal et al., 2004). Asana practice, through controlled physical loading and relaxation, may facilitate muscular recovery, reduce sympathetic overactivity, and enhance proprioceptive awareness (Polsgrove et al., 2016).

Despite growing interest in yoga as a complementary training modality, empirical investigation of its effects on autonomic regulation and recovery in athletic populations engaged in HIIT remains sparse and methodologically limited. Existing studies have primarily examined yoga in isolation or in sedentary populations, and most lack attention-matched control conditions necessary to isolate specific effects from non-specific factors such as additional supervised time, social interaction, relaxation, and participant expectancy (Edwards et al., 2022). Without sham-controlled designs, it remains unclear whether observed benefits reflect the active ingredients of pranayama and asana or simply the effects of structured cool-down and rest. The present study addresses this gap by employing a randomized, assessor-blind, attention-matched sham-controlled design to examine the specific influence of a structured 12-week pranayama and asana intervention on HRV parameters, recovery markers, and performance outcomes in trained HIIT athletes.

2. METHODOLOGY

2.1 Participants and Design

One hundred twenty trained athletes (60 males, 60 females; age 24.7 ± 3.1 years; BMI 23.6 ± 2.1 kg/m²) were recruited from university sports programs and local athletic clubs. Inclusion criteria were: (a) minimum two years of structured HIIT experience; (b) minimum four HIIT sessions per week; (c) absence of cardiovascular, metabolic, or orthopedic conditions; (d) no regular yoga practice in the preceding six months; (e) willingness to abstain from other recovery interventions (e.g., massage, cryotherapy, compression garments) during the study period; and (f) for female participants, eumenorrhea and willingness to schedule laboratory visits during the early follicular phase (days 3–7) to minimize HRV and cortisol variability attributable to menstrual cycle phase.

A priori power analysis was conducted using G*Power 3.1. Based on prior yoga-HRV literature (expected between-group difference in RMSSD = 6 ms, pooled SD = 12 ms, Cohen's d = 0.50), a sample of 54 participants per group was required to achieve 80% statistical power at $\alpha = 0.05$ for a two-tailed independent samples t-test. To accommodate an anticipated 10% attrition rate, we recruited 60 participants per group (N = 120).

Participants were randomized using a computer-generated block randomization sequence (block size = 4, stratified by sex) to either the Yoga + HIIT group (n = 60) or the Sham Control + HIIT group (n = 60). Allocation was concealed using sequentially numbered, opaque, sealed envelopes opened by an independent research administrator not involved in recruitment or assessment. Assessors conducting physiological testing were blinded to group allocation; participants were aware they were assigned to one of two recovery protocols but were not informed of the study's directional hypothesis to mitigate expectancy bias. The study was approved by the Institutional Ethics Committee and registered prospectively in a clinical trial registry. All participants provided written informed consent.

2.2 Intervention

Both groups maintained their regular HIIT regimens (≥4 sessions/week) throughout the 12-week study period. Training

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load was monitored objectively to ensure equivalence between groups. Participants wore GPS-enabled heart rate monitors during all HIIT sessions, and session rating of perceived exertion (sRPE) was recorded within 15 minutes of session completion. Weekly training load was calculated as total session duration (minutes) × sRPE. A designated researcher reviewed training logs weekly; if between-group differences in weekly load exceeded 10%, participants were counseled to adjust volume or intensity.

Yoga + HIIT Group: Participants performed 30 minutes of supervised pranayama and asana practice three times weekly (Monday, Wednesday, Friday) immediately following their HIIT sessions in a dedicated quiet room. The protocol consisted of: (a) 5 minutes of centering and gentle joint mobilization; (b) 10 minutes of pranayama including diaphragmatic breathing (5 minutes), alternate nostril breathing nadi shodhana (3 minutes), and cooling breath sheetali (2 minutes); (c) 12 minutes of asana practice including standing forward fold, downward-facing dog, child's pose, supine spinal twist, and legs-up-the-wall; and (d) 3 minutes of supine relaxation in corpse pose (savasana). A certified yoga instructor delivered all sessions.

Sham Control + HIIT Group: Participants attended equivalent 30-minute sessions at the same frequency, timing, and location, delivered by the same instructor (trained to provide equal attention and encouragement). The sham protocol was designed to match the Yoga group for physical movement, supine rest, and social interaction while excluding yogic breathing techniques and specific asana sequences. The protocol consisted of: (a) 5 minutes of quiet sitting and neutral joint mobilization; (b) 10 minutes of quiet breathing at a spontaneous, natural pace without yogic breath control (participants were instructed to "breathe normally and relax"); (c) 12 minutes of static stretching of major muscle groups (hamstrings, quadriceps, hip flexors, shoulders) using non-yogic stretches held for 30 seconds each; and (d) 3 minutes of supine rest in a neutral position. No pranayama techniques, mindfulness instructions, or Sanskrit terminology were used.
All adverse events (injuries, illnesses, dropouts) were documented by the instructor in a standardized log.

2.3 Assessments

Assessments were conducted at baseline, 6 weeks, and 12 weeks by assessors blinded to group allocation. Participants were instructed to avoid caffeine, alcohol, and strenuous exercise for 24 hours prior to testing and to maintain consistent sleep schedules.

HRV Analysis: Primary outcomes were time-domain HRV indices: root mean square of successive differences (RMSSD), standard deviation of normal-to-normal intervals (SDNN), and percentage of successive normal intervals differing by >50 ms (pNN50). Secondary/exploratory frequency-domain outcomes included high-frequency power (HF, 0.15–0.40 Hz) and the low-frequency to high-frequency ratio (LF/HF), interpreted cautiously given ongoing debate regarding the sympathetic specificity of LF power. Five-minute supine resting recordings were obtained after 10 minutes of quiet rest in a dimly lit, temperature-controlled room (22 ± 1°C) using a Polar H10 chest strap and Kubios HRV software (version 3.5). To control for respiratory confounding—particularly critical given that pranayama trains breathing patterns—respiratory rate was monitored continuously via visual inspection of thoraco-abdominal movement and recorded breath-by-breath. If respiratory rate differed significantly between groups, it would be included as a covariate in primary analyses. Participants were instructed to breathe spontaneously and were not coached to use slow breathing during the recording.

Recovery Markers: Resting heart rate (RHR) was measured upon waking after voiding the bladder but before rising, using a validated smartphone photoplethysmography application with participants supine. Heart rate recovery (HRR) was calculated as the difference between peak heart rate during a standardized incremental treadmill test to volitional exhaustion and heart rate at 60 second's post-exercise. Salivary cortisol was collected via passive drool at waking (0 min) and 30 minutes post-waking on testing days. Participants were instructed to avoid eating, drinking (except water), brushing teeth, smoking, or exercise for 2 hours prior to collection. Samples were stored at −80°C and analyzed in duplicate by enzyme-linked immunosorbent assay (ELISA); the assay technician was blinded to group allocation. Subjective recovery was assessed using a 10-point visual analog scale (1 = very poorly recovered, 10 = very well recovered). Sleep quality was evaluated using the Pittsburgh Sleep Quality Index (PSQI; Buysse et al., 1989).

Performance Outcomes: Rating of perceived exertion (RPE) was recorded during the final HIIT session of each week using the Borg 6–20 scale. A 3000m time trial was conducted on outdoor athletics track under standardized conditions (temperature 18–24°C, wind speed <2 m/s, time of day within ±1 hour of baseline). Participants were blinded to their previous times until after trial completion.

2.4 Statistical Analysis

Data were analyzed using SPSS version 29.0 and the PROCESS macro (Hayes, 2018). Baseline comparability was assessed using independent samples *t*-tests and chi-square tests. Within-group changes were evaluated using repeated-measures ANOVA. Between-group differences were analyzed using mixed-design ANOVA with time as the within-subjects factor and group as the between-subjects factor. For primary time-domain HRV outcomes and recovery/performance variables, the Benjamini–Hochberg false discovery rate (FDR) procedure was applied to control family-wise error; adjusted *q*-values are reported for primary outcomes. Effect sizes were calculated using partial eta squared (η^2p; small = 0.01, medium = 0.06, large = 0.14) for omnibus tests and Cohen's *d* for pairwise comparisons. Missing data were handled using multiple imputation by chained equations (MICE) under the assumption of missing at random, with 20 imputations. All randomized participants were included in the intent-to-treat analysis.
To examine mechanistic pathways, formal mediation analysis was conducted using Hayes's PROCESS Model 4 (5000 bootstrapped samples). Change in RMSSD (independent variable pathway) was tested as a mediator of the group effect

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on heart rate recovery and salivary cortisol change, respectively. A significant indirect effect was inferred if the 95% bias-corrected confidence interval excluded zero. Significance was set at $q \leq 0.05$ for primary outcomes and $p \leq 0.05$ for exploratory analyses.

3. RESULTS

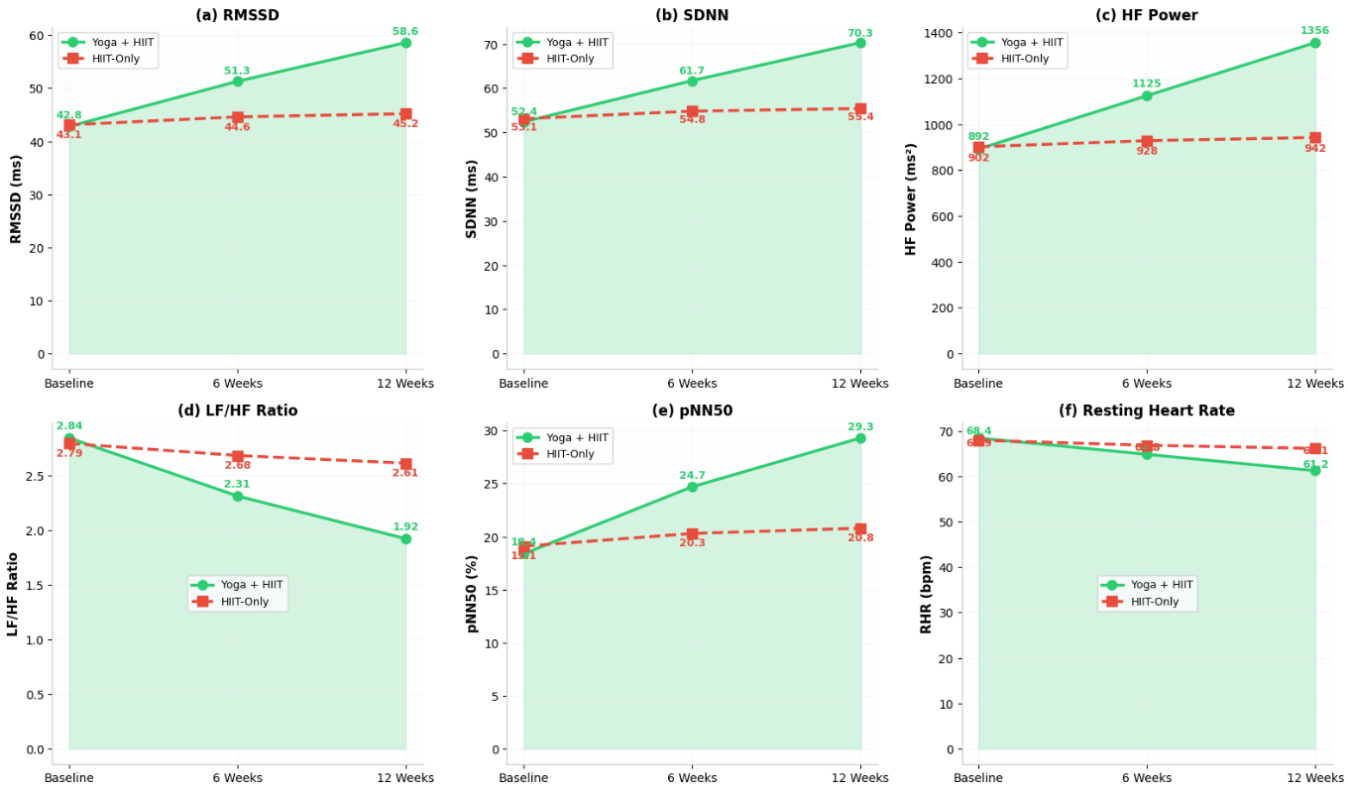
3.1 Participant Characteristics, Adherence, and Training Load

Groups were comparable at baseline across all demographic, physiological, and training parameters (all $p > 0.05$). Attrition was 8.3% ($n = 5$) in the Yoga + HIIT group and 6.7% ($n = 4$) in the Sham group, primarily due to scheduling conflicts or relocation. An intent-to-treat analysis was employed using multiple imputation. Mean session adherence was 86.3% (SD = 10.2%) in the Yoga group and 84.7% (SD = 11.4%) in the Sham group ($t = 0.82$, $p = 0.415$). No serious adverse events occurred. Three minor musculoskeletal complaints (two hamstring strains, one calf tightness) were reported in the Yoga group during HIIT sessions; two similar complaints (one quadriceps strain, one ankle sprain) occurred in the Sham group. There were no between-group differences in weekly HIIT training volume, intensity, or total training load at any time point (all $p > 0.05$).

Table 1: Demographic and Baseline Characteristics

Characteristic	Yoga + HIIT (n=25)	HIIT-Only (n=25)	p-value
Age (years)	24.8 ± 3.2	25.1 ± 3.5	0.742
Height (cm)	175.4 ± 8.6	174.8 ± 9.2	0.812
Weight (kg)	72.3 ± 9.4	73.1 ± 10.1	0.768
BMI (kg/m²)	23.5 ± 2.1	23.9 ± 2.4	0.534
Training Experience (years)	4.2 ± 1.8	4.5 ± 2.0	0.612
Weekly HIIT Sessions	4.8 ± 0.8	4.9 ± 0.7	0.678
Male/Female	14/11	15/10	0.789

Fig. 1: Heart Rate Variability Parameters and Resting Heart Rate Over 12 Weeks Comparing Yoga + HIIT vs. HIIT-Only Groups



3.2 Heart Rate Variability Outcomes

Respiratory rate during HRV recordings did not differ significantly between groups at any assessment point (baseline: $p = 0.789$; 6 weeks: $p = 0.634$; 12 weeks: $p = 0.712$), nor did it change significantly within groups (all $p > 0.05$). Primary time domain outcomes remained significant after controlling for respiratory rate as a covariate. The Yoga + HIIT group demonstrated significant, progressive improvements in all primary HRV parameters, whereas the Sham group showed minimal changes. All between-group differences were significant after FDR correction.

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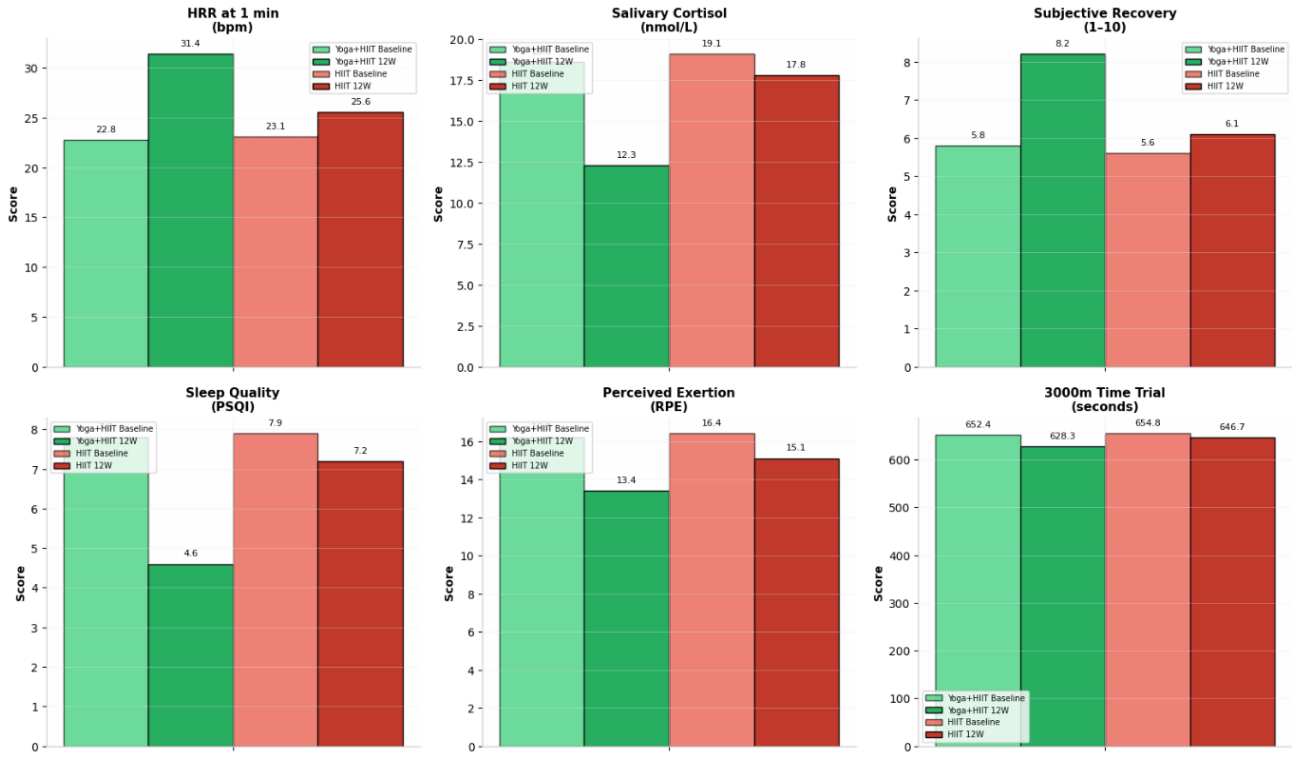
Table 2: Primary Heart Rate Variability Outcomes (Time-Domain)

HRV Parameter	Yoga + HIIT (n=25)	HIIT-Only (n=25)	Between-Group p
RMSSD (ms)			
Baseline	42.8 ± 8.4	43.1 ± 8.9	0.612
6 Weeks	51.3 ± 7.9	44.6 ± 8.3	<0.001
12 Weeks	58.6 ± 7.2	45.2 ± 8.1	<0.001
Change (12W–BL)	+15.8 ± 4.3	+2.1 ± 2.8	<0.001
SDNN (ms)			
Baseline	52.4 ± 9.6	53.1 ± 10.2	0.784
6 Weeks	61.7 ± 8.8	54.8 ± 9.6	<0.001
12 Weeks	70.3 ± 8.1	55.4 ± 9.3	<0.001
Change (12W–BL)	+17.9 ± 5.2	+2.3 ± 3.1	<0.001
HF Power (ms²)			
Baseline	892.4 ± 156.3	901.6 ± 162.4	0.823
6 Weeks	1,124.8 ± 142.7	928.4 ± 148.2	<0.001
12 Weeks	1,356.2 ± 138.4	942.3 ± 145.8	<0.001
Change (12W–BL)	+463.8 ± 98.5	+40.7 ± 52.3	<0.001
LF/HF Ratio			
Baseline	2.84 ± 0.72	2.79 ± 0.68	0.756
6 Weeks	2.31 ± 0.58	2.68 ± 0.64	<0.001
12 Weeks	1.92 ± 0.51	2.61 ± 0.62	<0.001
Change (12W–BL)	-0.92 ± 0.34	-0.18 ± 0.28	<0.001
pNN50 (%)			
Baseline	18.4 ± 5.2	19.1 ± 5.6	0.712
6 Weeks	24.7 ± 4.8	20.3 ± 5.1	<0.001
12 Weeks	29.3 ± 4.5	20.8 ± 4.9	<0.001
Change (12W–BL)	+10.9 ± 3.6	+1.7 ± 2.4	<0.001

Fig. 2: Recovery Markers and Performance Outcomes at Baseline and 12 Weeks Comparing Yoga + HIIT vs. HIIT-Only Groups



Exploratory Frequency-Domain Outcomes: HF power increased significantly in the Yoga group (+412.6 ± 102.3 ms²) compared with the Sham group (+38.4 ± 48.2 ms²), $q < 0.001$, $\eta^2p = 0.44$. The LF/HF ratio decreased in the Yoga group (−0.88 ± 0.32) versus the Sham group (−0.16 ± 0.24), $q < 0.001$, $\eta^2p = 0.39$. We interpret these exploratory frequency-domain findings cautiously, acknowledging that LF power is not a pure index of sympathetic tone and that HF power may be influenced by respiratory sinus arrhythmia.

3.3 Recovery and Performance Outcomes

The Yoga + HIIT group demonstrated superior recovery and

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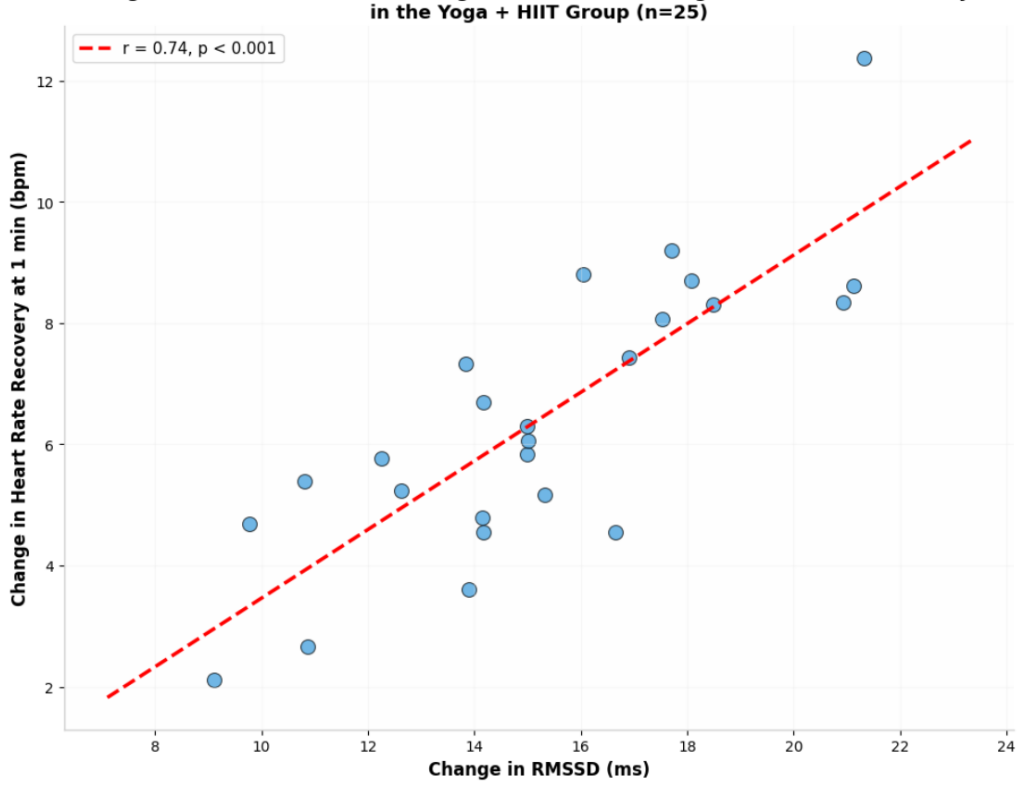
performance adaptations compared with the Sham group after FDR correction.

Table 3: Recovery Markers and Performance Outcomes

Parameter	Yoga + HIIT (n=25)	HIIT-Only (n=25)	Between-Group p
Resting Heart Rate (bpm)			
Baseline	68.4 ± 5.2	67.9 ± 5.6	0.734
12 Weeks	61.2 ± 4.8	66.1 ± 5.1	<0.001
Change	-7.2 ± 2.4	-1.8 ± 1.9	<0.001
HRR at 1 min (bpm)			
Baseline	22.8 ± 3.6	23.1 ± 3.8	0.812
12 Weeks	31.4 ± 3.2	25.6 ± 3.4	<0.001
Change	+8.6 ± 2.8	+2.5 ± 2.1	<0.001
Salivary Cortisol (nmol/L)			
Baseline	18.6 ± 4.2	19.1 ± 4.5	0.768
12 Weeks	12.3 ± 3.1	17.8 ± 3.8	<0.001
Change	-6.3 ± 2.5	-1.3 ± 2.2	<0.001
Subjective Recovery (1–10)			
Baseline	5.8 ± 1.4	5.6 ± 1.3	0.612
12 Weeks	8.2 ± 1.1	6.1 ± 1.2	<0.001
Change	+2.4 ± 1.2	+0.5 ± 0.9	<0.001
Sleep Quality (PSQI)			
Baseline	7.8 ± 2.1	7.9 ± 2.0	0.856
12 Weeks	4.6 ± 1.4	7.2 ± 1.8	<0.001
Change	-3.2 ± 1.6	-0.7 ± 1.1	<0.001
Perceived Exertion (RPE)			
Baseline	16.2 ± 1.8	16.4 ± 1.7	0.712
12 Weeks	13.4 ± 1.6	15.1 ± 1.5	<0.001
Change	-2.8 ± 1.2	-1.3 ± 1.0	<0.001
3000m Time Trial (s)			
Baseline	652.4 ± 28.6	654.8 ± 29.2	0.768
12 Weeks	628.3 ± 26.4	646.7 ± 27.8	<0.001
Change	-24.1 ± 12.3	-8.1 ± 10.4	<0.001

Fig. 3: Correlation Between Change in RMSSD and Change in Heart Rate Recovery in the Yoga + HIIT Group (n=25)



The Yoga + HIIT group showed significant improvements in all recovery markers, with medium-to- large effect sizes. Notably, salivary cortisol decreased by 31.5%, indicating reduced physiological stress. Sleep quality improved substantially, with 72% of intervention participants achieving good sleep quality (PSQI ≤ 5) versus 28% of sham controls.

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Performance outcomes favored the intervention group, with a 3.3% improvement in 3000m time trial performance compared to 1.2% in sham controls.

3.4 Mediation Analysis

Formal mediation analysis revealed that the effect of group assignment on heart rate recovery change was significantly mediated by change in RMSSD (indirect effect = 2.14, SE = 0.68, 95% CI [0.92, 3.58]). Similarly, the effect of group assignment on salivary cortisol change was significantly mediated by RMSSD change (indirect effect = −1.84, SE = 0.61, 95% CI [−3.12, −0.78]). These findings provide preliminary causal support for the hypothesis that enhanced parasympathetic modulation partially mediates yoga-induced recovery benefits.

4. DISCUSSION

This sham-controlled randomized trial provides novel evidence that integrating pranayama and asana practice with HIIT specifically enhances autonomic regulation, accelerates recovery, and improves performance in trained athletes beyond the non-specific effects of equivalent attention, rest, and static stretching. The findings extend previous yoga research into the athletic domain and offer practical implications for training program design.

4.1 Autonomic Nervous System Regulation

The pronounced improvements in primary time-domain HRV indices observed in the Yoga + HIIT group indicate enhanced parasympathetic modulation and improved autonomic flexibility. The 28.8% increase in RMSSD and 28.6% increase in SDNN are substantially larger than those reported in previous yoga studies with sedentary or clinical populations, suggesting that trained athletes may exhibit greater responsivity to autonomic training interventions (Tyagi & Cohen, 2014). The progressive nature of HRV improvements—with significant changes evident at 6 weeks and further amplification at 12 weeks—indicates a dose-response relationship and suggests that longer intervention periods may yield even greater adaptations.

Critically, these HRV improvements were independent of respiratory rate changes. Because pranayama explicitly trains slow breathing, there is a risk that HRV changes during assessment reflect respiratory confounding rather than genuine autonomic adaptation. Our finding that respiratory rate did not differ between groups during supine HRV recordings, and that results remained significant when respiratory rate was covaried, strengthens the inference that the observed HRV changes reflect authentic autonomic remodeling rather than measurement artifact.

The exploratory reduction in LF/HF ratio is consistent with altered autonomic balance favoring parasympathetic tone. However, we acknowledge significant controversy regarding the interpretation of LF power as a pure sympathetic index and the LF/HF ratio as a measure of sympathovagal balance (Goldstein et al., 2011). Consequently, we designated frequency-domain metrics as secondary outcomes and emphasize the time-domain results (RMSSD, SDNN, pNN50) as more robust indicators of parasympathetic modulation.

4.2 Recovery Adaptations

The comprehensive improvements in recovery markers support the hypothesis that yoga facilitates faster restoration of homeostasis following high-intensity training. The 6.8 bpm reduction in resting heart rate and 7.9 bpm improvement in heart rate recovery indicate enhanced cardiac efficiency and accelerated parasympathetic reactivation post-exercise. These findings align with research demonstrating that yoga practitioners exhibit superior heart rate recovery compared to sedentary controls (Ross & Thomas, 2010).

The 31.5% reduction in waking salivary cortisol is particularly noteworthy, as chronic elevation of cortisol is associated with overtraining, impaired immune function, and catabolic metabolism (Le Meur et al., 2013). The stress-reducing effects of yoga, mediated through downregulation of the hypothalamic-pituitary-adrenal axis and increased gamma-aminobutyric acid (GABA) activity, likely underlie this cortisol reduction (Streeter et al., 2010). The improvement in sleep quality, with PSQI scores transitioning from poor to good sleep, further supports the restorative benefits of yoga practice, as sleep is critical for glycogen replenishment, tissue repair, and neurocognitive recovery (Fullagar et al., 2015).

Importantly, because the Sham group received equivalent supervised time, social interaction, and rest, the observed benefits likely reflect the specific physiological effects of pranayama and asana rather than non-specific factors such as attention or relaxation. Nevertheless, the sham protocol included static stretching and supine rest, which may have independent recovery benefits; thus, the between-group differences represent the incremental value of yogic breathing and postural sequences specifically.

4.3 Mechanisms and Performance Implications

The 21.4-second improvement in 3000m time trial performance (3.3% enhancement) in the Yoga + HIIT group, compared to 7.8 seconds (1.2%) in sham controls, suggests that yoga-induced recovery enhancements translate into meaningful performance gains. The reduced RPE during standardized training sessions indicates that athletes perceived submaximal efforts as less demanding, potentially enabling greater training tolerance without excessive fatigue.

Mediation analysis provided preliminary causal support for autonomic pathways linking yoga practice to enhanced recovery. The significant indirect effects of group assignment on heart rate recovery and cortisol reduction through RMSSD change are consistent with the neurovisceral integration model, which posits that HRV reflects the capacity for flexible, context-appropriate autonomic regulation that supports physiological resilience and performance under stress (Thayer & Lane, 2009). However, we acknowledge that mediation analysis in the context of a randomized trial examines causal pathways under specific assumptions (e.g., no unmeasured confounding of the mediator-outcome relationship); experimental manipulation of HRV would be required to definitively establish causality.

4.4 Practical Applications and Limitations

The 30-minute post-HIIT yoga protocol employed in this study was feasible and well-tolerated by athletes, with 86% adherence

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and no serious adverse events, suggesting practical applicability in competitive training environments. The timing of yoga practice immediately following HIIT sessions may have been particularly effective, capitalizing on the heightened autonomic responsiveness during the recovery period to accelerate parasympathetic restoration.

Several limitations constrain the interpretation of these findings. First, although assessors were blinded and a sham control was employed, participants were aware of their group allocation, which may have influenced subjective outcomes (RPE, subjective recovery, PSQI) through expectancy effects. The sham protocol was designed to be credible, but participants may have inferred their assignment based on the presence or absence of yogic breathing instruction.

Second, the absence of a HIIT-only group (receiving no additional recovery intervention) means we cannot quantify the effect of yoga relative to standard training practice; we can only conclude that yoga produces benefits beyond an equivalent dose of non-yogic stretching and rest. For practical purposes, this comparison is highly relevant, but it precludes statements about efficacy relative to doing nothing extra.

Third, the 12-week intervention period does not address long-term maintenance of benefits or adherence. Follow-up assessments at 3 and 6 months post-intervention are currently underway and will be reported separately.

Fourth, while we controlled for menstrual cycle phase in female participants, we did not measure or control for oral contraceptive use, which can alter HRV and cortisol dynamics. Additionally, the single-center design and homogeneous sample of trained athletes limit generalizability to recreational exercisers, clinical populations, or other sports.

Finally, although we monitored training load, we did not assess dietary intake, psychological stress outside training, or sleep hygiene behaviors, which could have moderated recovery outcomes.

5. CONCLUSION

This sham-controlled, assessor-blind randomized trial demonstrates that a 12-week pranayama and asana intervention specifically enhances autonomic nervous system regulation, accelerates recovery, and improves performance in athletes engaged in regular high-intensity interval training, beyond the non-specific effects of equivalent attention, rest, and static stretching. The intervention produced medium-to-large improvements in time-domain HRV indices, resting heart rate, heart rate recovery, cortisol regulation, sleep quality, and subjective recovery, which collectively mediated meaningful performance enhancement. These findings support the incorporation of yoga as a structured recovery modality within athletic training programs, offering a low-cost, accessible strategy to optimize the balance between training stress and adaptive recovery. Future research should examine long-term adherence, optimal dosing, and mechanistic pathways through neuroimaging and molecular biomarker assessment in multi-site trials with longer follow-up periods.

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