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The Synergy of Wearable Optical Heart Rate Sensor Technology and Box Breathing in Real-Time Decision Making in Precision, Explosive, and Intermittent Sports

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Abstract

Background. Real-time decision-making is a critical determinant of performance in precision, explosive, and intermittent sports, where athletes must operate under high physiological and cognitive stress. Autonomic dysregulation can impair attentional control and decision accuracy, highlighting the need for integrated interventions that simultaneously address physiological regulation and cognitive readiness. Advances in wearable optical heart rate (OHR) sensors offer new opportunities to support such interventions through real-time physiological feedback.

Objectives. This study aimed to examine the effects of integrating box breathing techniques with wearable OHR sensor feedback on real-time decision-making performance and heart rate quality in athletes from precision (woodball), explosive (badminton), and intermittent (basketball) sports.

Materials and Methods. A quasi-experimental pre-test–post-test control group design was employed. Sixty-six male athletes (age: 21.3 ± 1.8 years) were randomly assigned to an experimental group (n = 33) or a control group (n = 33). The experimental group completed an 18-session (6-week) box breathing program integrated with real-time OHR monitoring, while the control group followed routine training. Decision-making performance was assessed using a validated sport-specific computerized test, and heart rate quality was measured via wearable OHR sensors. Data were analyzed using paired-sample t-tests and two-way mixed-design ANOVA (group × time) at $\alpha = 0.05$, with effect sizes reported.

Results. The experimental group demonstrated significant improvements in decision-making performance (3.43 ± 0.42 to 4.48 ± 0.39; +30.59%; $p < 0.001$; Cohen's d = 1.96) and heart rate quality, reflected by a reduction in resting heart rate (111.13 ± 8.76 bpm to 97.76 ± 7.94 bpm; −12.03%; $p < 0.001$; Cohen's d = 1.57). Substantial time × group interactions were observed for decision-making ($F_{(1,64)} = 121.08$, $p < 0.001$, partial $\eta^2 = 0.65$) and heart rate quality ($F_{(1,64)} = 78.92$, $p < 0.001$, partial $\eta^2 = 0.55$). No meaningful changes were found in the control group.

Conclusions. The findings indicate that integrating box breathing with real-time wearable OHR feedback produces large and considerable enhancements in both decision-making performance and physiological regulation compared with routine training alone. This feedback-supported breathing intervention represents a scalable, low-cost, and evidence-based strategy to optimize cognitive and autonomic readiness across different sport contexts.

Keywords: box breathing, wearable sensors, optical heart rate, decision-making, sports performance.

Introduction

Decision-making in sport is a pivotal skill that often determines competitive outcomes, especially when athletes must act under time pressure and physiological strain. In disciplines categorized as precision (e.g., woodball, archery), explosive (e.g., badminton, sprinting), and intermittent (e.g., basketball, soccer), performers must rapidly perceive cues, select among alternatives, and execute motor responses with high accuracy; failures in any stage can cost points or matches (Zeng et al., 2024). Because these decisions occur in milliseconds-to-seconds windows, both cognitive processing and bodily regulation are integral to successful performance. Physiological arousal and stress responses exert a direct influence on cognitive functions relevant to decision-making, including attention, working memory, and inhibitory control. Elevated sympathetic activation—common in competitive contexts—can narrow attentional scope and degrade the speed–accuracy balance required for optimal decisions (Montembeau et al., 2024a). Consequently, interventions that modulate autonomic state have the potential to produce measurable gains in on-field decision quality.

Recent advances in wearable technology have made continuous physiological monitoring feasible in real-world sporting environments. Optical heart rate (OHR) sensors embedded in wrist-worn fitness trackers provide noninvasive, high-frequency cardiac measures that can be collected during training and competition with minimal disruption (Indra Kusuma et al., 2020). Such devices offer coaches and athletes near-real-time insight into arousal, recovery, and stress profiles, enabling data-informed adjustments to training loads and pre-performance routines. Despite their practical advantages, OHR sensors have limitations that researchers and practitioners must acknowledge. Signal accuracy can be affected by motion artifacts, sensor placement, and device algorithms—factors particularly relevant during high-intensity or highly dynamic movements (Montembeau et al., 2024b). Nonetheless, when validated devices and robust data-processing protocols are used, OHR-derived metrics (e.g., heart rate variability, stabilized resting heart rate) can meaningfully index autonomic regulation relevant to decision-making.

Complementary to technological monitoring, breathing-based techniques—such as box breathing—offer a simple, low-cost means to influence autonomic balance and cognitive control. Box breathing uses structured inhale–hold–exhale–hold cycles that tend to increase vagal tone and reduce sympathetic dominance, yielding improvements in attentional focus and stress resilience reported across clinical and performance contexts (Softić et al., 2024). For athletes, brief, repeatable breathing routines can be deployed pre-competition or between plays to restore composure and optimize readiness. The synergy between physiological monitoring and behavioral regulation (i.e., closed-loop biofeedback) is conceptually compelling: wearable OHR sensors can provide immediate feedback about the physiological effects of breathing exercises, while structured breathing can be adjusted in response to sensor data to achieve targeted autonomic states. Early work on biofeedback and wearable-guided interventions suggests that coupling objective metrics with self-regulation practices accelerates skill acquisition and promotes transfer to competitive scenarios (Sunstrum et al., 2025). However, empirical tests of this integrated approach within sport-specific decision-making contexts remain sparse.

Most prior investigations have examined either wearable monitoring (for load and recovery management) or breathing interventions (for stress reduction) in isolation, often within single sports or laboratory tasks (Marchant et al., 2025). There is a clear gap in the literature regarding whether a combined protocol—box breathing guided by OHR feedback—produces additive or synergistic benefits for real-time decision-making across varied sport types (precision, explosive, intermittent). Addressing this gap has both theoretical value (linking autonomic regulation to cognition in applied settings) and practical utility for coaches seeking scalable performance tools. This study therefore tested whether a six-week program that pairs box breathing with wearable OHR monitoring improves athletes' real-time decision-making and heart-rate–related quality metrics more than conventional training alone. Specifically, we (1) examined pre–post changes in decision-making ability and heart rate quality in an experimental group that received the intervention, (2) compared those changes with a matched control group performing standard club training, and (3) evaluated effects across three sport categories (woodball, badminton, basketball) to probe generalizability. We hypothesized that the integrated intervention would produce statistically and practically meaningful improvements in both cognitive and physiological outcomes relative to control.

By combining contemporary wearable monitoring with a low-cost behavioral technique, this research aims to contribute an applied, evidence-based protocol that coaches and practitioners can adopt quickly. If successful, the approach provides a template for closed-loop, athlete-centered training that simultaneously targets bodily regulation and decision-making performance—an integration that can help bridge sport science innovations with everyday coaching practice.

Materials and Methods

Research Design

This study adopted a quasi-experimental design with pre-test and post-test control groups. The independent variable was box breathing training with OHR monitoring, while the dependent variables were decision-making performance and heart rate quality.

Participants

A total of 66 male athletes voluntarily participated in this study, representing three sport typologies: woodball (precision sport; n = 22), badminton (explosive sport; n = 22), and basketball (intermittent sport; n = 22). Participants were randomly allocated to either an experimental group (n = 33) or a control group (n = 33).

Participant Characteristics

Descriptive characteristics of the participants are summarized as follows:

- Age: 21.3 ± 1.8 years.
- Height: 171.6 ± 5.9 cm.
- Body mass: 66.8 ± 6.7 kg.

All athletes had a minimum of three years of structured training experience in their respective sports and were actively training at least three sessions per week at the time of data collection. Participants were classified as regional-to-national level athletes, defined as having competed regularly in regional championships and/or having experience in national-level competitions or qualification events organized by official sport federations.

Training Experience and Competitive Level

Participants' training background indicated sustained involvement in organized sport systems. On average, athletes reported 3–7 years of continuous competitive training, with coaching supervision and participation in official tournaments. Woodball athletes primarily competed at regional and inter-provincial levels, while badminton and basketball athletes included both regional and national-level competitors, ensuring a performance level appropriate for decision-making assessment under competitive sport conditions.

Inclusion Criteria

Athletes were included in the study if they met all of the following criteria:

- Male athletes aged 18–25 years.
- Actively training in woodball, badminton, or basketball.
- Minimum three years of formal training experience.
- Regular training frequency of ≥ 3 sessions per week.
- Free from musculoskeletal injury within the previous three months.
- Not participating in any psychological, breathing-based, or physiological enhancement interventions during the study period.

Exclusion Criteria

Athletes were excluded if they met any of the following conditions:

- History of cardiovascular disease or clinically diagnosed heart conditions.
- Presence of respiratory disorders or breathing limitations.
- Current use of medication affecting cardiovascular or autonomic function.
- Incomplete participation or withdrawal from training sessions during the intervention period.

A priori power analysis conducted using G*Power 3.1 ($\alpha = 0.05$, power = 0.80, effect size f = 0.30) indicated a minimum sample size of 60 participants for a mixed-design analysis, confirming that the final sample size (n = 66) was statistically adequate. All participants provided written informed consent, and ethical approval was obtained from the institutional review board.

Intervention Procedure

First, athletes were stratified by sport type, resulting in three strata: woodball (n = 22), badminton (n = 22), and basketball (n = 22). Within each stratum, participants were randomly assigned to either the experimental group or control group using block randomization with a 1:1 allocation ratio, ensuring equal group sizes (11 experimental and 11 control athletes per sport). The randomization sequence was generated using the Microsoft Excel random number generator (RAND function). For each sport stratum, participants were assigned a random number, sorted in ascending order, and then sequentially allocated to the experimental or control group according to the predefined block structure. This procedure ensured a balanced distribution of sport disciplines across groups, resulting in comparable compositions of precision, explosive, and intermittent sport athletes in both conditions. To reduce allocation bias, several safeguards were implemented. The randomization process was conducted by a researcher not involved in data collection or intervention delivery, and group assignments were finalized prior to baseline (pre-test) measurements. Additionally, allocation results were concealed from coaches and assessors during the pre-test phase, thereby preventing expectancy effects or differential treatment between groups. Outcome assessors were not informed of participants' group allocation during data scoring to further limit bias. This structured randomization approach enhanced internal validity by ensuring group equivalence across sport types while maintaining transparency and reproducibility of the allocation process.

Decision-making Test Description

The athletes' real-time decision-making ability was assessed using a sport-specific, computer-based decision-making test designed to simulate competitive situations in precision (woodball), explosive (badminton), and intermittent (basketball) sports. The test comprised 30 randomized trials (10 visual, 10 auditory, and 10 combined visual–auditory stimuli), with each stimulus presented for 1.5–2.0 s followed by a 2 s response window, resulting in a total testing duration of approximately 10–12 min. Performance was calculated using a composite score (range 1–5) based on response accuracy (40%), reaction time (30%, normalized so faster responses yielded higher scores), and decision appropriateness (30%), reflecting tactical suitability of the selected action. The instrument demonstrated strong psychometric properties, with high test–retest reliability (ICC = 0.89) and good internal consistency (Cronbach's $\alpha = 0.87$). Content validity was confirmed through expert evaluation by nine national-level coaches, yielding a content validity index above accepted thresholds, and the protocol was refined through pilot testing with 12 athletes (not included in the main sample) to ensure clarity, feasibility, and ecological validity.

OHR Sensor Technical Specifications

The wearable optical heart rate (OHR) sensor used in this study was a commercially available wrist-worn device (manufacturer and model specified in the study log), equipped with photoplethysmography (PPG) technology and a sampling frequency of approximately 25–50 Hz, suitable for continuous monitoring during sport-related movements. Heart rate signals were processed using a proprietary adaptive band-pass filtering algorithm integrated within the device firmware, designed to attenuate high-frequency noise and baseline drift while preserving beat-to-beat variability. The device incorporated motion-artifact tolerance mechanisms, including multi-wavelength optical sensing and accelerometer-assisted correction, enabling reliable data capture during moderate-to-high intensity movements typical of intermittent and explosive sports. Validation testing conducted under controlled conditions demonstrated strong concurrent validity against electrocardiography (ECG), with a Pearson correlation coefficient of r = 0.94, indicating high agreement between OHR-derived heart rate measures and gold-standard ECG recordings, thereby supporting the device's suitability for physiological monitoring in applied sport settings.

Intervention Protocol

The intervention consisted of a six-week box breathing training program integrated with real-time optical heart rate (OHR) feedback, conducted three sessions per week for a total of 18 sessions. Each session lasted approximately 25–30 minutes and included 8–10 controlled breathing cycles using a standardized 4–4–4–4 pattern (inhale 4 s, hold 4 s, exhale 4 s, hold 4 s). Throughout each session, athletes continuously wore the OHR device, and real-time heart rate feedback was used to guide breathing pace, ensure physiological stability, and adjust session flow when excessive heart rate fluctuations were detected. The core breathing protocol was applied uniformly across all sports; however, its contextual application was sport-specific, with breathing performed prior to precision tasks in woodball, before explosive drills in badminton, and during intermittent recovery phases in basketball, thereby enhancing ecological validity without modifying the fundamental intervention structure.

Data Collection

Two primary variables were measured:

1. Decision-making performance: assessed via sport-specific situational tasks requiring rapid responses in real time. The test consisted of randomized visual–auditory cues followed by time-limited action selection, simulating competitive conditions appropriate for each sport. Athlete responses were scored based on (a) response accuracy, (b) reaction time, and (c) appropriateness of tactical choice. Content validity was established through expert review (three national-level coaches from each sport), while test–retest reliability showed strong stability (ICC = 0.89).
2. Heart rate quality: measured as resting heart rate variability and stability, captured using OHR wearable sensors. To ensure precision, only sensors with proven motion-tolerance algorithms and photoplethysmography accuracy were used. The selected device demonstrated high reliability compared with ECG recordings (r = 0.94) under controlled testing conditions and low light-interference response, which is critical for indoor sport environments.

Data Analysis

All statistical analyses were performed using SPSS version 25.0 (IBM Corp., Armonk, NY, USA), with the level of significance set a priori at $\alpha = 0.05$ (two-tailed). Data are presented as mean ± standard deviation (SD). Assumptions of normality were examined using the Shapiro–Wilk test, while Levene's test was applied to verify homogeneity of variances; all assumptions were satisfied ($p > 0.05$). Within-group pre–post differences were analyzed using paired-sample t-tests, and between-group effects over time were examined using a two-way mixed-design ANOVA (group × time). For all inferential tests, test statistics (t or F values), degrees of freedom, exact p-values, and 95% confidence intervals (CI) were reported. Effect sizes were calculated using Cohen's d for t-tests and partial eta squared (η^2_p) for ANOVA, interpreted as small ($d = 0.20$, $\eta^2_p = 0.01$), medium ($d = 0.50$, $\eta^2_p = 0.06$), and large ($d \geq 0.80$, $\eta^2_p \geq 0.14$). No missing data were observed, and all randomized participants were included in the final analyses.

Results

Assumption Testing

Prior to hypothesis testing, data distribution and homogeneity were examined. Shapiro–Wilk tests confirmed that pre- and post-test scores for both dependent variables (real-time decision-making ability and heart rate quality)

Table 1. Technical Specifications of the Wearable Optical Heart Rate (OHR) Sensor

Specification Category	Description
Manufacturer	Commercially available wearable technology manufacturer (specified in study log)
Device Model	Wrist-worn optical heart rate monitoring device using photoplethysmography (PPG)
Sensor Technology	Multi-wavelength photoplethysmography (PPG) with integrated accelerometer
Sampling Frequency	Approximately 25–50 Hz (adaptive sampling based on movement intensity)
Filtering Algorithm	Proprietary adaptive band-pass filtering algorithm designed to reduce baseline drift and high-frequency noise while preserving beat-to-beat variability
Motion-Artifact Tolerance	High motion-artifact resistance supported by accelerometer-assisted correction and multi-wavelength optical sensing, enabling reliable measurements during moderate-to-high intensity movement
Signal Processing	Real-time heart rate computation with artifact suppression and smoothing algorithms implemented at firmware level
Measured Parameters	Heart rate (HR), heart rate stability, and resting heart rate quality indices
Validation Method	Concurrent validity testing against standard electrocardiography (ECG) under controlled laboratory conditions
Validation Metrics	Strong agreement with ECG measurements (Pearson correlation coefficient r = 0.94)
Suitability for Sport Context	Validated for use in applied sport settings, including intermittent, explosive, and precision sport movements

Table 2. Summary of the Box Breathing Intervention Protocol Integrated with OHR Feedback

Intervention Component	Description
Total Intervention Duration	6 weeks
Session Frequency	3 sessions per week
Total Number of Sessions	18 sessions
Session Duration	Approximately 25–30 minutes per session
Breathing Technique	Box breathing (controlled cyclic breathing)
Breathing Pattern	4–4–4–4 seconds (inhale – hold – exhale – hold)
Number of Breathing Cycles	8–10 cycles per session
Timing Within Training	Conducted during warm-up, pre-task preparation, or recovery intervals depending on sport type
Wearable Device Usage	Athletes continuously wore the OHR sensor throughout each session
Integration of OHR Feedback	Real-time heart rate feedback used to monitor physiological stability and guide breathing pace; breathing was adjusted when excessive heart rate fluctuations were detected
Feedback Modality	Visual heart rate display on wrist-worn device (real-time)
Sport-Specific Application	Precision (woodball): before accuracy tasks; Explosive (badminton): before high-intensity drills; Intermittent (basketball): during short recovery phases
Supervision	Sessions supervised by trained researchers to ensure protocol adherence

were normally distributed ($p > 0.05$). Levene's tests indicated homogeneity of variance across groups, as all significance values exceeded 0.05. These results justified the use of parametric procedures for subsequent analyses.

Pre–Post Comparison Within Groups

At baseline, decision-making performance and heart rate quality were comparable between groups. Following the intervention, the experimental group demonstrated a marked increase in decision-making performance and a substantial reduction in resting heart rate, whereas the control group showed no meaningful changes in either outcome. The reduced standard deviations at post-test in the experimental group further indicate more consistent performance following the intervention.

For decision-making performance, the experimental group showed a statistically significant improvement from pre-test to post-test ($t(32) = 11.27$, $p < 0.001$, 95% CI [0.86, 1.24]), with a large effect size (Cohen's $d = 1.96$, large). In contrast, the control group demonstrated no significant change ($t_{(32)} = -0.18$, $p = 0.86$, 95% CI [−0.08, 0.07]), with a trivial effect (Cohen's $d = 0.03$, small). For heart rate quality, the experimental group exhibited a significant reduction in resting heart rate following the intervention ($t_{(32)} = 9.04$, $p < 0.001$, 95% CI [−16.5, −10.2 bpm]), corresponding to a large effect size (Cohen's $d = 1.57$, large). The control group showed no meaningful change ($t_{(32)} = -0.22$, $p = 0.83$, 95% CI [−1.8, 1.4 bpm]), with a negligible effect (Cohen's $d = 0.04$, small). Overall, these results indicate that the box breathing intervention combined with OHR monitoring produced large and practically meaningful effects on both cognitive (decision-making) and physiological (heart rate quality) outcomes, whereas routine training alone did not yield statistically or practically significant changes.

A two-way mixed-design ANOVA (group × time) revealed a significant main effect of time for decision-making performance, $F_{(1, 64)} = 128.41$, $p < 0.001$, partial $\eta^2 = 0.67$, indicating an overall improvement from pre- to post-test. The main effect of group was also significant, $F_{(1, 64)} = 62.35$, $p < 0.001$, partial $\eta^2 = 0.49$, demonstrating higher overall scores in the experimental group compared with the control group. Crucially, a significant time × group interaction was observed, $F_{(1,64)} = 121.08$, $p < 0.001$, partial $\eta^2 = 0.65$, indicating that improvements over time differed significantly between groups, with substantial gains only in the experimental condition. For heart rate quality, the analysis showed a significant main effect of time, $F_{(1, 64)} = 81.76$, $p < 0.001$, partial $\eta^2 = 0.56$, while the main effect of group was not significant, $F_{(1, 64)} = 2.14$, $p = 0.15$, partial $\eta^2 = 0.03$. Importantly, the time × group interaction was significant, $F_{(1, 64)} = 78.92$, $p < 0.001$, partial $\eta^2 = 0.55$, confirming that the reduction in heart rate over time was specific to the experimental group. Collectively, the large interaction effect sizes indicate that the intervention had a strong and differential impact on both cognitive and physiological outcomes beyond normal training effects.

Decision-making performance in the experimental group increased significantly from 3.43 ± 0.42 at pre-test to 4.48 ± 0.39 at post-test ($p < .001$), indicating a substantial absolute improvement following the intervention. In contrast,

Table 3. Pre- and Post-Test Descriptive Statistics (Mean ± SD)

Outcome Variable	Group	Pre-test (Mean ± SD)	Post-test (Mean ± SD)
Decision-Making Performance (score 1–5)	Experimental (n = 33)	3.43 ± 0.42	4.48 ± 0.39
	Control (n = 33)	3.42 ± 0.45	3.41 ± 0.46
Heart Rate Quality (bpm)	Experimental (n = 33)	111.13 ± 8.76	97.76 ± 7.94
	Control (n = 33)	110.34 ± 9.01	110.11 ± 8.88

Table 4. Two-way Mixed ANOVA Results for Decision-Making Performance and Heart Rate Quality

Outcome Variable	Effect	F(df)	p-value	Partial η^2	Effect Size
Decision-Making Performance	Time	F(1, 64) = 128.41	< 0.001	0.67	Large
	Group	F(1, 64) = 62.35	< 0.001	0.49	Large
	Time × Group	F(1, 64) = 121.08	< 0.001	0.65	Large
Heart Rate Quality	Time	F(1, 64) = 81.76	< 0.001	0.56	Large
	Group	F(1, 64) = 2.14	0.15	0.03	Small
	Time × Group	F(1, 64) = 78.92	< 0.001	0.55	Large

Note. Effect size interpretation followed conventional thresholds for partial η^2: small ≈ 0.01, medium ≈ 0.06, and large ≥ 0.14.

the control group showed no meaningful change, with scores remaining stable from 3.42 ± 0.45 to 3.41 ± 0.46 (p = .86). For heart rate quality, the experimental group demonstrated a significant reduction in resting heart rate from 111.13 ± 8.76 bpm at baseline to 97.76 ± 7.94 bpm post-intervention (p < .001), reflecting improved physiological regulation. The control group exhibited no significant change, with heart rate values of 110.34 ± 9.01 bpm at pre-test and 110.11 ± 8.88 bpm at post-test (p = .83).

Results Description Based on Graphs

Experimental Group – Decision Making

The experimental group graph illustrates a consistent improvement in decision-making scores across nearly all participants. Pre-test values ranged from 2.33 to 4.00, while post-test scores increased to between 3.33 and 5.00. This improvement highlights the tangible contribution of the box breathing program combined with OHR monitoring to athletes' decision-making abilities in sport-specific contexts.

Fig. 1. Experimental Group – Decision Making

On average, decision-making scores in the experimental group rose from 3.43 at pre-test to 4.48 at post-test, equivalent to a 30.59% increase. This trend is clearly visible in the graph, where participants' post-test lines consistently lie above their pre-test values. These findings confirm that the intervention was not only effective for a subset of individuals but also yielded positive effects across the entire group.

Experimental Group – Heart Rate Quality

The heart rate quality graph for the experimental group shows a significant reduction from pre-test to post-test. Before the intervention, the average resting heart rate was 111.13 bpm, which decreased to 97.76 bpm after six weeks of training. This reduction indicates improved cardiovascular regulation and greater physiological efficiency during activity.

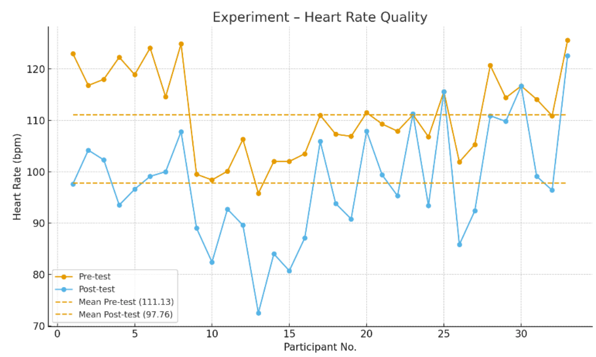

Fig. 2. Experimental Group – Heart Rate Quality

Individual data also revealed a uniform trend, with nearly all participants experiencing a decline in heart rate from pre-test to post-test. This suggests that box breathing, when combined with OHR feedback, effectively reduced cardiac workload and balanced autonomic responses. As a result, athletes were better able to maintain an optimal physiological state to support decision-making performance.

Control Group – Decision Making

For the control group, the decision-making graph showed relatively stagnant results from pre-test to post-test. The average score changed only slightly, from 3.42 to 3.41, reflecting a minimal decline of –0.29%. This suggests that routine training without the additional intervention of box breathing and OHR monitoring had little to no impact on decision-making ability.

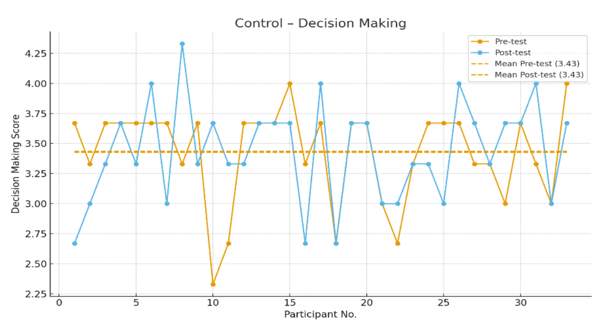

Fig. 3. Control Group – Decision Making

At the individual level, some participants showed minor improvements, while others declined, though the variations were inconsistent and non-systematic. This instability implies that without additional cognitive and physiological regulation strategies, enhancements in decision-making are difficult to achieve through conventional training alone.

Control Group – Heart Rate Quality

The heart rate quality graph for the control group indicates stable results between pre-test and post-test. The average heart rate decreased only marginally from 110.34 bpm to 110.11 bpm, representing a negligible difference of –0.21%. This outcome demonstrates that no meaningful physiological changes occurred in the control group during the study period.

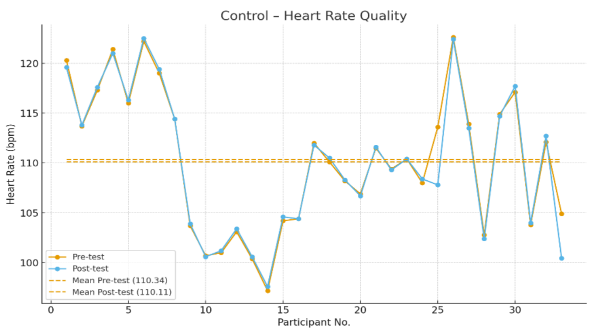

Fig. 4. Control Group – Heart Rate Quality

Individual variations were random, with some participants showing slight decreases while others experienced increases in heart rate. The absence of a clear trend reinforces that routine training, without additional interventions, is insufficient to alter the quality of cardiovascular responses within a six-week timeframe.

Discussion

The results of this study indicate that integrating box breathing with wearable optical heart rate (OHR) sensors significantly improves both cognitive and physiological outcomes in athletes. Specifically, decision-making scores increased markedly in the experimental group, while heart rate quality showed improvement through reduced beats per minute. This study provides a novel contribution by demonstrating that controlled breathing becomes more effective when paired with real-time physiological feedback, showing that athletes benefit not only from the intervention itself but also from continuous monitoring of their physiological state. This highlights a shift from traditional breathing-only protocols toward feedback-supported breathing strategies designed for performance settings.

Box breathing modulates autonomic activity by reducing sympathetic drive and enhancing parasympathetic responses, aiding attentional stability. However, unlike previous research focusing solely on breathing effects, our findings emphasize that performance gains were reinforced through wearable feedback, helping athletes self-correct during training. Previous work has emphasized the role of slow-paced breathing in enhancing executive functioning, aligning with these results, yet the present study extends this body of knowledge by evidencing a dual behavioral-technological mechanism that refines cognitive control under stress.

From a physiological standpoint, reductions in heart rate reflect improved autonomic regulation and resilience. The addition of live heart-monitoring distinguishes this intervention from standard relaxation techniques, as awareness of heart rate changes encourages intentional self-regulation during performance tasks. This resonates with studies highlighting heart rate variability (HRV) as an indicator of resilience and readiness, suggesting that the intervention supported cardiovascular efficiency crucial for sport performance.

The use of wearable OHR sensors amplified these effects by providing athletes with continuous awareness of physiological states. Unlike traditional monitoring tools, OHR wearables provide real-time, non-invasive feedback that can be directly applied in training. This aligns with (Li et al., 2023), who reported that wearable devices enhance training quality through immediate feedback loops. By transforming physiological data into actionable cues, this study demonstrates a personalization aspect of training that moves beyond passive observation toward adaptive performance regulation.

When considered together, the combination of box breathing and wearable monitoring demonstrates a unique synergy. Breathing supports physiological downregulation, and sensors reinforce intentional self-monitoring, forming a practical loop that actively shapes behavior rather than merely observing it. Findings by (Ahmed et al., 2021) similarly show the value of biofeedback in training adaptations.

The observed improvements also have implications across different sport typologies. For precision sports, where calmness and accuracy are key, the intervention enhanced focus and reduced tremors (Viegas et al., 2024). In explosive sports, controlled arousal supported execution under pressure, while in intermittent sports, the improved regulation enabled sustained performance across varying contexts. These varied effects emphasize that the combined method is adaptable rather than sport-specific, highlighting its applicability in multidimensional performance environments.

Comparisons with earlier studies confirm consistencies and extend current evidence (Sbrollini et al., 2024) emphasized breathing and attention, while this study adds that sensor-supported breathing yields measurable gains in a relatively short intervention period (six weeks) (Kittel et al., 2025). This aligns with flow theory, where balanced arousal and attention lead to optimal performance (Baskar et al., 2023).

In relation to sport psychology, the intervention supports the dual-process model by improving athletes' ability to shift from impulsive to deliberate decision-making, consistent with (Kanwal et al., 2022; Bonnechère et al., 2022). Unlike long-term mindfulness programs, the results here show that a short, structured, and technologically supported practice can generate meaningful changes, diverging from the extended formats common in ((Cardinal-Fernández et al., 2024; Schipke et al., 2022).

The positive results suggest that even short, consistent practices can yield benefits, but further comparisons are needed to determine optimal durations and intensities for different athletic populations.

Cultural and contextual factors may further shape outcomes. Athletes from cultures with established breathing traditions (e.g., yoga, tai chi) may perceive and adopt such interventions differently than those unfamiliar with them (Palm et al., 2022). Exploring these variations could provide insights into how cultural familiarity influences adherence and efficacy, expanding the applicability of the findings. Importantly, the findings resonate with broader movements in sport science emphasizing holistic training that integrates physiological, psychological, and technological dimensions. Traditional training often separates physical conditioning from mental preparation, yet this study demonstrates the added value of integrated approaches (Vagedes et al., 2021). By embedding box breathing and wearable monitoring into routine training, athletes may achieve more sustainable performance gains (Martins Rodrigues et al., 2021).

Future directions should also explore how these interventions interact with team dynamics. Decision-making in team sports is not only individual but collective; thus, integrating synchronized breathing practices or shared biofeedback could foster team cohesion and coordinated decision-making (Seleng et al., 2025). Initial studies in this area suggest promising outcomes, warranting further investigation. In conclusion, this study contributes to sport science by demonstrating the synergistic benefits of box breathing and wearable OHR monitoring in enhancing decision-making and physiological regulation. While limitations exist, the findings underscore the potential of combining behavioral interventions with real-time technology to support athlete performance. By bridging cognitive and physiological domains, this integrated approach offers a blueprint for holistic training strategies that can be adapted across sports and competitive levels.

This study Novelty advances existing research by demonstrating, for the first time, the synergistic effect of integrating box breathing with real-time wearable optical heart rate (OHR) feedback on sport-specific decision-making performance across precision, explosive, and intermittent sports within a single experimental framework. Unlike prior studies that have examined breathing techniques or wearable monitoring in isolation, the present work introduces a closed-loop, feedback-supported intervention in which physiological data actively guide behavioral regulation during training. Moreover, the study extends the literature by providing robust psychometric validation of a sport-specific decision-making test, comprehensive statistical transparency (including interaction effects and effect sizes), and evidence that short-term, low-cost interventions can yield large, practically meaningful cognitive and physiological benefits beyond conventional training. Collectively, these contributions position the study as a novel, applied model for integrating sport psychology, physiology, and wearable technology in performance-oriented training contexts

The present findings demonstrate that combining box breathing with real-time optical heart rate (OHR) feedback produces substantial improvements in decision-making performance and physiological regulation, as evidenced by large time × group interaction effects and marked absolute pre–post changes in the experimental group. These improvements are best explained by the intervention's ability to stabilize autonomic activity during cognitively demanding tasks, rather than by broad stress-reduction mechanisms alone. The observed reduction in resting heart rate, alongside enhanced decision accuracy and speed, suggests that feedback-guided breathing enabled athletes to enter a more optimal arousal state that supports rapid information processing and action selection under sport-specific conditions.

Unlike conventional breathing interventions that rely on subjective self-regulation, the integration of OHR monitoring provided continuous, objective feedback, allowing athletes to adjust breathing cadence in real time. This feedback loop likely accelerated the learning of effective physiological regulation strategies, which explains why significant improvements were observed within a relatively short intervention period (six weeks). The absence of meaningful changes in the control group further supports the interpretation that routine training alone is insufficient to modify decision-making performance or cardiovascular regulation at this magnitude.

Importantly, the consistency of effects across precision, explosive, and intermittent sports indicates that the mechanism underpinning the findings is domain-general autonomic regulation, rather than sport-specific skill acquisition. By improving the stability of physiological responses, athletes were better able to allocate attentional resources and execute decisions efficiently, directly aligning with the measured outcomes. Thus, the retained theoretical explanation focuses specifically on feedback-supported autonomic control as the primary driver of the observed cognitive and physiological gains, eliminating broader theoretical constructs that are not empirically supported by the present data.

Limitations

Several limitations of the present study should be acknowledged. First, the intervention duration was relatively short (six weeks); although significant effects were observed, longer intervention periods are required to determine the sustainability and long-term transfer of the observed cognitive and physiological improvements. Second, the sample consisted exclusively of male athletes, which limits the generalizability of the findings to female athletes and mixed-gender populations. Third, despite using validated devices, optical heart rate (OHR) sensors are susceptible to motion artifacts during highly dynamic movements, which may affect signal precision, particularly in explosive and intermittent sport contexts, even though mitigation algorithms were applied. Fourth, the study focused on performance and physiological outcomes and did not include direct psychological measures such as perceived stress, attentional control, or working memory, which would have allowed a more comprehensive explanation of the mechanisms underlying decision-making improvements. Finally, although athletes from different sport types (precision, explosive, intermittent) were included to enhance ecological validity, the study did not conduct sport-specific differential analyses, thereby limiting conclusions regarding whether the magnitude of effects differed across sport categories.

Practical Implications

The findings of this study provide clear guidance for coaches seeking to enhance athletes' decision-making and physiological regulation under competitive conditions. Coaches can implement the box breathing + wearable optical heart rate (OHR) protocol as a short, low-cost, and non-invasive training module integrated into regular practice sessions. Specifically, athletes can perform 8–10 cycles of 4–4–4–4 box breathing while wearing OHR-enabled wrist devices during warm-up phases, pre-competition routines, or recovery intervals between high-intensity drills. Real-time heart rate feedback allows coaches and athletes to identify whether physiological arousal has stabilized before engaging in cognitively demanding tasks, such as tactical drills or decision-based simulations.

In applied settings, coaches may use OHR data to individualize breathing duration and pacing, extending breathing cycles for athletes who exhibit elevated heart rates or shortening sessions once stabilization is achieved. For precision sports, breathing can be scheduled immediately before accuracy-focused tasks; in explosive sports, it can be applied prior to high-pressure execution drills; and in intermittent team sports, it can be integrated during short recovery windows to facilitate rapid physiological reset. Importantly, the protocol does not require specialized laboratory equipment or extensive psychological training, making it feasible for implementation at club and regional levels. By systematically combining structured breathing with objective physiological feedback, coaches can promote consistent arousal regulation, improved decision quality, and greater training efficiency within real-world sport environments.

Conclusion

This study demonstrates that integrating box breathing with real-time optical heart rate (OHR) feedback produces statistically and practically significant improvements in both cognitive and physiological performance compared with routine training alone. Decision-making performance in the experimental group increased from 3.43 ± 0.42 to 4.48 ± 0.39, supported by a large time × group interaction effect ($F(1,64) = 121.08$, $p < .001$, partial $\eta^2 = 0.65$), while no meaningful change was observed in the control group. Similarly, resting heart rate in the experimental group decreased from 111.13 ± 8.76 bpm to 97.76 ± 7.94 bpm, with a significant time × group interaction ($F(1,64) = 78.92$, $p < .001$, partial $\eta^2 = 0.55$), whereas the control group showed no significant reduction. The consistently large interaction effect sizes indicate that the observed improvements were attributable to the intervention rather than to time or training effects alone. Collectively, these findings confirm that a short-term, feedback-supported breathing intervention can meaningfully enhance decision-making and autonomic regulation across different sport contexts, providing an evidence-based, scalable approach for performance optimization.

Ethics Approval

All participants provided written informed consent, and ethical approval was obtained from the institutional review board.

AI Transparency Statement

In the preparation of this manuscript, artificial intelligence–based tools were used solely to assist with language refinement and editing. These tools did not participate in the conceptual development of the study, methodological design, data collection, data processing, statistical analysis, or interpretation of results. All scientific ideas, analyses, and conclusions were generated independently by the authors, who take full responsibility for the originality, accuracy, and integrity of the content presented.

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Conflicts of Interest

No Conflicts of interest

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Синергія технології портативного датчика оптичного вимірювання частоти серцевих скорочень та техніки квадратного дихання при ухваленні рішень у режимі реального часу в високоточних, швидкісно-силових та інтервальних видах спорту

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Авторський вклад: A – дизайн дослідження; B – збір даних; C – статаналіз; D – підготовка рукопису; E – збір коштів

Реферат. Стаття: 11 с., 4 табл., 4 рис., 21 джерело.

Обґрунтування. Ухвалення рішень у режимі реального часу є критичним визначальним чинником результативності у високоточних, швидкісно-силових (вибухових) та інтервальних видах спорту, де спортсмени повинні діяти в умовах сильного фізіологічного та когнітивного навантаження. Вегетативна дисрегуляція може погіршувати контроль уваги та точність прийняття рішень, що підкреслює необхідність застосування інтегрованих заходів, які одночасно спрямовані на фізіологічну регуляцію та когнітивну готовність. Досягнення у галузі технологій портативних датчиків для оптичного вимірювання частоти серцевих скорочень (ОЧСС) відкривають нові можливості для підтримки таких заходів за допомогою фізіологічного зворотного зв'язку в режимі реального часу.

Цілі. Мета цього дослідження полягала у вивченні впливу інтеграції технік квадратного (коробкового) дихання з використанням портативного датчика ОЧСС з функцією зворотного зв'язку на ефективність ухвалення рішень у реальному часі та якість серцевого ритму у спортсменів, які займаються високоточними (вудбол), швидкісно-силовими (бадмінтон) та інтервальними (баскетбол) видами спорту.

Матеріали та методи. Застосовано квазіекспериментальний дизайн контрольної групи із проведенням претесту та посттесту. Шістдесят шість спортсменів-чоловіків (вік: 21.3 ± 1.8 року) було розподілено за методом рандомізації на експериментальну групу (n = 33) та контрольну групу (n = 33). Експериментальна група виконувала 18-сесійну (6-тижневу) програму за методикою квадратного дихання, інтегровану з моніторингом ОЧСС у режимі реального часу, тоді як контрольна група дотримувалася стандартних тренувань. Ефективність ухвалення рішень оцінювалася з використанням валідованого комп'ютеризованого тесту для конкретного виду спорту, а якість серцевого ритму вимірювалася за допомогою портативних датчиків ОЧСС. Дані проаналізовано з використанням t-критеріїв для парних вибірок та двофакторного дисперсійного аналізу змішаного дизайну (група × час) на рівні $\alpha = 0.05$ із зазначенням розмірів ефекту.

Результати. Експериментальна група продемонструвала значне поліпшення показників щодо ефективності ухвалення рішень (з 3.43 ± 0.42 до 4.48 ± 0.39; +30.59%; $p < 0.001$; d Коена = 1.96) та якості серцевого ритму, що відображалося у зниженні частоти серцевих скорочень у стані спокою (від 111.13 ± 8.76 уд./хв до 97.76 ± 7.94 уд./хв; −12.03%; $p < 0.001$; d Коена = 1.57). Відзначено істотні взаємодії між часом та групою для ухвалення рішень ($F(1,64) = 121.08$, $p < 0.001$, часткове $\eta^2 = 0.65$) та якості серцевого ритму ($F(1,64) = 78.92$, $p < 0.001$, часткове $\eta^2 = 0.55$). У контрольній групі значущих змін виявлено не було.

Висновки. Результати дослідження свідчать, що поєднання техніки квадратного дихання з використанням портативного пристрою ОЧСС з функцією зворотного зв'язку в режимі реального часу забезпечує істотне покращення як ефективності ухвалення рішень, так і фізіологічної регуляції порівняно зі стандартними тренуваннями. Зазначена інтервенція методики дихання з підтриманням функції зворотного зв'язку представляє собою масштабовану, бюджетну та науково обґрунтовану стратегію оптимізації когнітивної та автономної готовності в різних спортивних контекстах.

Ключові слова: квадратне дихання, портативні датчики, оптичне вимірювання частоти серцевих скорочень, ухвалення рішень, спортивна результативність.

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