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Original Scientific Article

High-Intensity Interval Training Outperforms Fartlek and Continuous Training in Aerobic and Running-Mechanics Adaptations: Evidence from Athletics Education

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Abstract

Background. Aerobic capacity and biomechanical efficiency are central determinants of performance in athletics. However, empirical evidence directly comparing different training modalities using an integrative assessment of physiological, biomechanical, and cardiovascular recovery variables remains limited, particularly within structured athletics training environments.

Objectives. This study aimed to compare the effectiveness of Fartlek, High Intensity Interval Training (HIIT), and Moderate Continuous Training (MCT) on aerobic capacity, running efficiency, and cardiovascular recovery in sports science students enrolled in athletics courses, thereby providing novel insight into evidence-based conditioning strategies relevant to athletics training.

Materials and Methods. A total of 102 sports science students taking athletics coursework were randomly assigned to HIIT ($n = 34$), Fartlek ($n = 34$), or MCT ($n = 34$). The eight-week intervention consisted of three weekly sessions. Measured outcomes included VO_2max, vVO_2max, running economy, stride mechanics, and heart rate recovery (HRR1–HRR3). Data were analyzed using paired t-tests, one-way ANOVA, LSD post-hoc tests, and effect size calculations (Cohen's d; partial η^2).

Results. All training models produced significant improvements across all parameters ($p < 0.001$). HIIT yielded the most substantial gains in VO_2max, vVO_2max, running economy, stride length, ground contact time, and HRR indices. ANOVA revealed significant between-group differences on all primary variables ($p < 0.001$; $\eta^2 = 0.27–0.47$), indicating the superior adaptive response of HIIT compared with Fartlek and MCT in the athletics training context.

Conclusions. The findings confirm that HIIT showed the greatest enhancements in aerobic capacity, mechanical running efficiency, and cardiovascular recovery among the training methods examined in this cohort of sports science students. Its superiority stems from structured high-intensity stimuli that maximize cardiovascular stress, mitochondrial adaptation, lactate tolerance, and neuromuscular recruitment. Further research should investigate responses in competitive athletes, extend intervention duration, and incorporate advanced metabolic and neuromuscular analyses to deepen understanding of HIIT-driven adaptations in athletics.

Keywords: fartlek training, high intensity interval training (HIIT), athletics training, aerobic capacity, running economy, stride mechanics, cardiovascular recovery, VO_2max.

Introduction

The aerobic capacity represented by maximal oxygen uptake (VO_2max) constitutes a central physiological determinant within athletics because it reflects the integrated function of the cardiovascular, respiratory, and skeletal muscle systems in supporting maximal oxidative energy production (Idnani et al., 2025; Kamarudin et al., 2024a). VO_2max not only denotes an athlete's fundamental work capacity but also shapes key performance-related variables such as running economy, maximal aerobic velocity (vVO_2max), lactate threshold tolerance, and inter-interval recovery efficiency

(Perdana et al., 2025; Sopyan et al., 2023). Accordingly, strength and conditioning (S&C) practitioners routinely employ VO_2max as a primary indicator for designing training programs that integrate endurance, speed, and biomechanical efficiency components (Fahmi Hidayat et al., 2025; Kamarudin et al., 2024).

Multiple aerobic training modalities have been examined across the literature and applied in athletic preparation, yet their adaptive responses show considerable variability (Z. Wang & Wang, 2024). For instance, (Satria et al., 2024) reported that both Fartlek and high-intensity interval training (HIIT) enhanced VO_2max in futsal players; however, the findings were derived from non-athletics populations and excluded biomechanical assessments or running economy metrics that are directly relevant to track performance. Similar results were documented by (Bermeo Guamán et al., 2023), who compared Fartlek with continuous running in recreational runners and found greater and faster improvements in VO_2max in the Fartlek group. Nevertheless, the absence of performance-specific measures such as race-pace velocity or stride efficiency limits the extent to which these findings can be translated to competitive athletics contexts (Bermeo Guamán et al., 2023).

Research by (Karthikeyan, 2025) on adolescent athletes likewise demonstrated VO_2max improvements following both Fartlek and continuous training, with Fartlek producing superior gains. This study was constrained by a small sample size and the lack of advanced performance indicators such as vVO_2max or competitive running speed. Similarly, (Festiawan et al., 2020) reported that Fartlek elicited higher VO_2max responses compared with interval training among football players, although differences did not reach statistical significance. Because the cohorts in these studies were not composed of trained runners and lacked analyses of recovery or movement economy, their applicability to athletics performance remains limited.

In long-distance running populations, (Susiono et al., 2025) observed that sprint interval training improved VO_2max and race performance such as 3,000-m time and time to exhaustion relative to conventional endurance training. However, the interpretability of these results is narrowed by (Tegegne Nigussie, 2024) the short intervention period (six weeks), small sample size, and absence of biomechanical or long-term recovery analyses. Another randomized trial in recreational runners reported differential responses to interval versus continuous training across running economy (RE), maximal aerobic speed (MAS), and stride kinematics, although the extremely small sample size and inadequate control of training intensity warrant caution when interpreting the findings (Tegegne Nigussie, 2024). A separate investigation by (Bici & Kasa, 2025) concluded that HIIT yielded larger gains in VO_2max compared with fartlek. Even so, substantial limitations including a sample of only eight participants, lack of cardiovascular-recovery or running-economy assessments, and no evaluation of sustained aerobic adaptation constrain the generalizability of the results. Thus, although HIIT and Fartlek appears promising in elevating aerobic capacity, definitive conclusions necessitate studies with stronger designs and broader physiological assessments.

Collectively, limitations across prior research underscore a critical scientific gap, particularly within the domain of athletics training. No comparative study has systematically evaluated HIIT and Fartlek using an integrated framework that simultaneously examines cardiorespiratory responses and performance-relevant variables. Key aspects including running economy, stride pattern and quality, heart rate recovery stability, and the transfer of training adaptations to race-specific speeds remain insufficiently investigated. Moreover, many earlier studies relied on simple pre-post designs without real-time intensity monitoring, making it difficult to characterize the actual physiological stimulus elicited by each training modality.

To address these shortcomings, the present study was designed as a controlled experiment with methodological rigor that surpasses previous investigations. Beyond comparing HIIT and Fartlek based on VO_2max, the study incorporated performance-critical indicators such as vVO_2max, running economy, stride efficiency, and cardiovascular recovery. The use of precise real-time intensity monitoring, comprehensive physiological instrumentation, and direct evaluation of adaptation transfer to race-related performance renders this study more holistic and more aligned with applied S&C practice in running-based events.

Additionally, the study included a larger sample size than most comparable research, thereby enhancing statistical power, effect-size precision, and generalizability. The combination of a rigorous experimental design, broad physiological coverage, and a more representative participant sample positions this study as a substantive contribution to evidence-based training methodology within athletics. However, given that the participants were non-athlete university students, the generalizability of these findings to trained or elite populations remains limited.

The novelty of this study can be articulated across three dimensions. First, to the authors' knowledge, this is the first investigation to directly compare HIIT and Fartlek in running athletes using an integrative analytical approach spanning VO_2max, cardiorespiratory responses, and biomechanical parameters. To maintain conceptual accuracy, these findings should be interpreted within the context of physical-education students rather than competitive athletes. Second, the simultaneous assessment of physiological variables (e.g., heart rate, recovery kinetics, oxidative capacity) and biomechanical variables (e.g., stride length, stride frequency, running economy) enables a more comprehensive understanding of training adaptation mechanisms. Third, the findings provide actionable implications for S&C coaches by identifying the training method that appears more effective within this sample, particularly in jointly enhancing aerobic capacity and race-specific performance, while acknowledging that these effects are bounded by the study design and population characteristics.

The scientific urgency of this research lies in its relevance to improving training prescriptions for university-level runners, a population for whom empirical evidence remains relatively limited. Accordingly, this study formulates explicit hypotheses to guide the comparative analysis: (H1) HIIT will produce greater improvements in VO_2max than Fartlek and continuous training among non-athlete university students; (H2) HIIT will elicit more pronounced adaptations in running biomechanics including stride parameters and running economy compared with the other training modalities; and (H3) HIIT will induce more favorable cardiorespiratory responses, reflected in heart-rate kinetics and recovery patterns, relative to Fartlek and continuous training. These hypotheses are aligned with previous literature and anchored in the physiological rationale underlying each training method.

Consequently, the primary aim of the present study is to evaluate and compare the effectiveness of High-Intensity Interval Training (HIIT) and Fartlek on cardiorespiratory responses and key performance indicators. Rather than claiming absolute superiority, the present analysis seeks to identify which training method demonstrates greater effectiveness within the constraints of this specific population and experimental design, thereby generating evidence-based recommendations for S&C practitioners working with similar student cohorts.

Materials and Methods

Participants

The study population comprised all active students enrolled in the sports science program at the Vocational Faculty of Universitas Negeri Surabaya. The eligible population consisted of 414 students who fulfilled administrative requirements and represented a broad distribution across early- to late-semester cohorts, with varying levels of physical activity experience and fitness status. Based on an a priori power analysis conducted using G*Power 3.1 with a moderate effect size (f = 0.25), α = 0.05, and a power of 0.80, the minimum required sample size was determined to be 102 participants. The available population was subsequently aligned with this requirement, and following a systematic selection process grounded in predefined inclusion and exclusion criteria, 102 students were recruited through simple random sampling and deemed eligible for participation.

To address these gaps, the present study implemented a structured comparative intervention with a sufficiently powered sample of sports science students. Given that the participants were non-athlete university students, all interpretations regarding training effectiveness are confined to similar populations and cannot be generalized to trained or elite athletes. The study sought not to claim absolute superiority of any model but rather to determine which modality demonstrates greater effectiveness within the scope of this population and research design.

The novelty of this investigation rests on three dimensions: (1) the direct comparison of HIIT, Fartlek, and continuous training using integrative physiological and biomechanical metrics, including VO_2max, heart-rate kinetics, stride parameters, and running economy; (2) the simultaneous analysis of cardiorespiratory and mechanical adaptations, enabling a more comprehensive interpretation of training-induced changes; and (3) the practical relevance of identifying the training model that produces the most meaningful improvements in a collegiate setting, providing evidence-based guidance for instructors and S&C practitioners.

Inclusion criteria consisted of being an active student aged 18–20 years, currently taking or having previously completed the Athletics course, being in good physical health, and not participating in any concurrent high-intensity training program that could confound physiological responses. Exclusion criteria encompassed sustaining an injury during the study period, attending fewer than 80% of the intervention sessions, the use of medications influencing physiological parameters, or any medical condition that could interfere with study procedures or compromise participant safety.

Study Design

This study employed an inferential experimental design using a randomized controlled trial (RCT) approach. A total of 102 participants were randomly allocated into three groups: the Fartlek group (n = 34), the High-Intensity Interval Training (HIIT) group (n = 34), and the Moderate Continuous Training (MCT) group, which served as the control condition (n = 34).

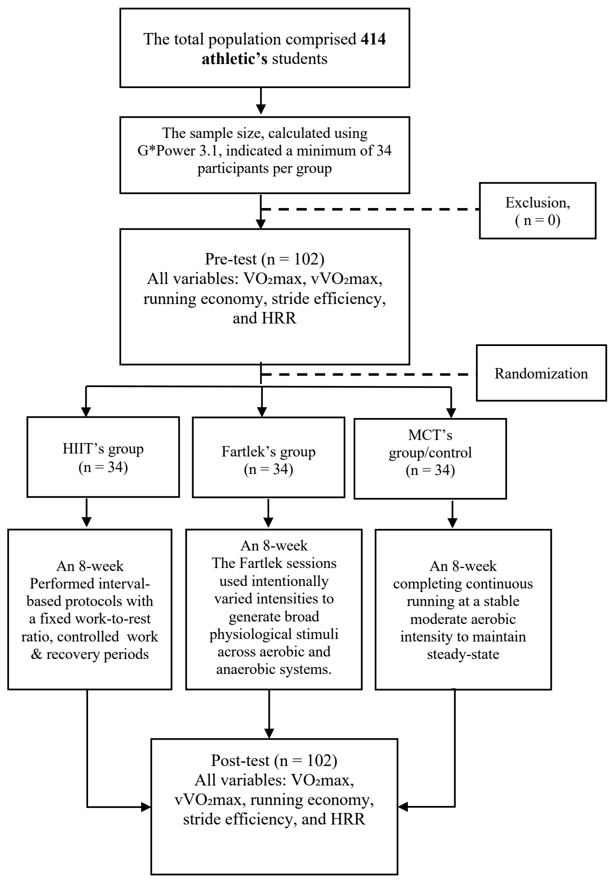

Fig. 1. Flowchart of the study

Research Procedures

The training intervention was administered over an eight-week period, with each session lasting 30–40 minutes. Each training modality featured a distinct intensity structure and session pattern designed to target improvements in aerobic capacity and mechanical running efficiency. Prior to the intervention, all participants completed a standardized pre-test assessment, and following six weeks of training, post-test evaluations were conducted using identical protocols to

Table 1. Summary of the Three-Intervention Groups Training Program

Group	Training Structure	Intensity	Session Duration	Weekly Frequency	Key Characteristics
Fartlek	Warm-up 10 minutes; Speed Play with a variety of sprints, mediums, short sprints, and recovery jogs; 10-minute cooldown	Varies 60–95% HRmax	50 minutes	3x/week	Random variations in rhythm and intensity to trigger aerobic and anaerobic adaptations
High Intensity Interval Training (HIIT)	1:1 interval training between the work phase and active rest	Working: 85–95% HRmax; Rest: 60–65% HRmax	50 minutes	3x/week	Focus on intense stimuli to increase VO2max and anaerobic capacity
MCT (Control)	Stable continuous road	65–75% HRmax	50 minutes	3x/week	Moderate aerobic exercise for basic cardiorespiratory capacity improvement

ensure comparability of physiological and biomechanical outcomes.

Each training session was structured according to the specific characteristics of the assigned modality. The Fartlek sessions employed a deliberately unstructured fluctuation of intensities to elicit broad and variable physiological stimuli across aerobic and anaerobic domains. The HIIT group performed interval-based protocols with a fixed work-to-rest ratio, ensuring consistent exposure to high-intensity bouts followed by controlled recovery periods. In contrast, the MCT group served as a comparative control, completing continuous running at a stable moderate aerobic intensity to maintain steady-state physiological loading.

Instruments

Maximal oxygen uptake (VO_2max) was assessed using the 20 m Shuttle Run Test (Beep Test), which provides an established field-based estimation of aerobic capacity based on the final level attained. Maximal aerobic velocity (vVO_2max) was measured through a progressive running test on a standard 400 m track, in which speed was increased every two minutes until participants were unable to maintain the prescribed pace. Running economy (RE) was evaluated by determining oxygen consumption during steady-state submaximal running (10–12 $km \cdot h^{-1}$) over a six-minute bout, with VO_2 values analyzed during minutes four through six to ensure metabolic stabilization. Stride efficiency was quantified using high-speed video capture or biomechanical sensors over a 30 m runway, enabling the extraction of stride length, stride frequency, and ground contact time (GCT). Heart rate recovery (HRR) was recorded following a three-minute high-intensity running bout at 85–90% of HRmax, during which HRpeak and recovery values at one, two, and three minutes post-exercise (HRR1, HRR2, HRR3) were obtained.

Ethical Clearance

This study was conducted in accordance with institutional and international ethical standards. Ethical approval was obtained from the Research Ethics Committee of Universitas ʽAisyiyah Surakarta (AISKA) under approval number KEP/UNI-AISKA/199/2025/010225, following initial endorsement by the Ethics Committee of the Faculty of Sport Sciences. All participants provided written informed consent after receiving a full explanation of the study objectives, procedures, potential benefits, and associated risks.

Data Analysis

All pre-test and post-test data were analyzed using IBM SPSS Statistics. Preliminary analyses included assessment of parametric assumptions through the Shapiro–Wilk test for normality and Levene's test for homogeneity of variance across groups. Within-group intervention effects for the Fartlek, High-Intensity Interval Training (HIIT), and MCT groups were examined using paired-samples t-tests to determine significant changes in VO_2max, vVO_2max, running economy, stride efficiency, and heart rate recovery (HRR). Between-group comparisons were conducted using independent-samples t-tests, while differences across the three training modalities were evaluated using one-way ANOVA on change scores (Δ). When ANOVA indicated significant effects ($p < 0.05$), Tukey's HSD post-hoc analyses were applied. To enhance practical interpretation, effect sizes were calculated using Cohen's d for t-tests and partial eta squared (η^2) for ANOVA. All results are presented as mean ± standard deviation, with statistical significance set at $p < 0.05$.

Result

A total of 102 participants met all eligibility criteria and were randomly allocated into the three intervention groups: Fartlek (n = 34), HIIT (n = 34), and Moderate Continuous Training (MCT) as the control group (n = 34). All participants completed the six-week intervention with full adherence and no dropout, allowing the analyses to be performed using a complete-case approach.

A total of 102 male sports science students aged 19–21 years were enrolled and randomly allocated into three training groups, each comprising 34 participants. Baseline

Table 2. Characteristics of Study Participants

Variable	HIIT Group (n = 34)	Fartlek Group (n = 34)	MCT Group (n = 34)
Gender	34 male	34 male	34 male
Age (years)	20.1 ± 0.6	20.0 ± 0.7	20.2 ± 0.5
BMI (kg/m²)	22.4 ± 1.8	22.1 ± 1.9	22.3 ± 1.7

characteristics were relatively homogeneous across groups, with an average age of approximately 20 years, body mass index within the ideal range, and physical activity levels classified as active (moderate to vigorous). This homogeneity strengthens the internal validity of the study by ensuring that observed differences in outcomes primarily reflect the effects of the respective training interventions.

Table 3. Participant Characteristics at Baseline

Variable	Fartlek (n = 34)	HIIT (n = 34)	MCT (n = 34)	p
Age (years)	20.6 ± 1.4	20.4 ± 1.5	20.5 ± 1.3	0.812
Body Mass Index (BMI; kg/m²)	22.1 ± 1.8	22.4 ± 2.1	22.0 ± 1.9	0.673
HRmax (bpm)	193.4 ± 6.1	194.1 ± 5.8	193.7 ± 6.3	0.889
Physical Readiness Questionnaire (PR-Q)	91.2 ± 4.8	92.0 ± 5.1	91.6 ± 4.6	0.742

All baseline variables showed $p > 0.05$, which means there was no significant difference between groups. Thus, all subjects were declared homogeneous before the intervention, in accordance with the principles of experimental research design and RCTs.

The results of the paired t-test showed that all three types of fartleek, HIIT, and MCT exercises resulted in significant improvements in the majority of physiological and biomechanical variables. Fartlek and HIIT resulted in the largest increases in VO_2max, vVO_2max, stride length, stride frequency, decreased running economy, and ground contact time, with both showing stronger changes than MCTs. Meanwhile, MCTs also showed significant improvements, but with smaller effects, and one of the variables (stride frequency) was not significant. In addition, the entire group showed significant improvements in cardiovascular recovery capacity (HRR1, HRR2, HRR3), with fartlek and HIIT again providing a greater adaptive response. Overall, fartlek and HIIT show higher effectiveness than MCTs in improving performance parameters and running efficiency.

Post-hoc LSD comparisons revealed distinct adaptive responses across the three training modalities. For VO_2max, HIIT demonstrated a small but statistically significant advantage over Fartlek ($\Delta = +0.80$, $p = 0.041$), while both HIIT and Fartlek produced markedly greater improvements than MCT ($\Delta = +3.35$ and $+4.15$, respectively; $p < 0.001$), indicating that interval-based training elicited superior aerobic gains relative to continuous moderate exercise.

Table 4. Within-Group Effects (Paired Sample t-Test) for Fartlek, HIIT, and MCT Groups

Variable	Group	Pre-test (Mean ± SD)	Post-test (Mean ± SD)	t-value	p-value
VO_2max (ml·kg^{-1}·min^{-1})	Fartlek	38.55 ± 3.20	43.20 ± 3.30	11.42	<0.001
	HIIT	38.60 ± 3.15	44.10 ± 3.28	13.92	<0.001
	MCT	38.10 ± 3.05	39.85 ± 3.20	5.44	<0.001
vVO_2max (km/h)	Fartlek	11.3 ± 1.1	13.0 ± 1.2	9.58	<0.001
	HIIT	11.4 ± 1.3	13.3 ± 1.2	11.01	<0.001
	MCT	11.2 ± 1.1	11.9 ± 1.2	4.88	<0.001
Running Economy (VO_2 ml/kg/min)	Fartlek	36.2 ± 2.7	34.1 ± 2.5	−6.44	<0.001
	HIIT	36.0 ± 2.9	34.0 ± 2.6	−7.44	<0.001
	MCT	36.1 ± 2.8	35.3 ± 2.7	−3.12	0.004
Stride Length (m)	Fartlek	1.22 ± 0.11	1.30 ± 0.12	7.01	<0.001
	HIIT	1.20 ± 0.10	1.29 ± 0.11	8.02	<0.001
	MCT	1.21 ± 0.10	1.24 ± 0.11	3.40	0.002
Stride Frequency (steps/min)	Fartlek	169.1 ± 7.8	173.4 ± 7.5	5.45	<0.001
	HIIT	168.2 ± 8.4	173.5 ± 8.0	6.77	<0.001
	MCT	168.0 ± 8.0	169.5 ± 7.8	2.02	0.051 (ns)
Ground Contact Time (ms)	Fartlek	249.2 ± 17.5	234.0 ± 16.9	−8.12	<0.001
	HIIT	247.8 ± 18.2	233.5 ± 17.8	−9.35	<0.001
	MCT	248.0 ± 18.6	243.2 ± 18.0	−3.55	0.001
HRR1 (bpm)	Fartlek	21.4 ± 4.6	28.2 ± 4.7	9.88	<0.001
	HIIT	21.1 ± 4.5	28.5 ± 4.9	11.55	<0.001
	MCT	21.2 ± 4.7	23.5 ± 4.9	3.88	<0.001
HRR2 (bpm)	Fartlek	34.8 ± 5.0	41.8 ± 4.9	10.01	<0.001
	HIIT	34.5 ± 5.2	42.0 ± 4.8	11.21	<0.001
	MCT	34.7 ± 5.1	37.8 ± 5.0	4.02	<0.001
HRR3 (bpm)	Fartlek	42.0 ± 5.1	49.1 ± 5.2	9.77	<0.001
	HIIT	42.3 ± 5.4	49.5 ± 5.1	10.68	<0.001
	MCT	42.0 ± 5.3	45.2 ± 5.1	3.91	<0.001

Table 5. LSD Post-Hoc Comparison Between Groups Based

Variable	Group Comparison	Mean Difference (Δ)	95% CI	p-value (LSD)
VO_2max (ml·kg^{-1}·min^{-1})	HIIT vs Fartlek	+0.80	0.02 to 1.58	0.041
	Fartlek vs MCT	+4.15	3.10 to 5.20	<0.001
	HIIT vs MCT	+3.35	2.30 to 4.40	<0.001
vVO_2max (km·h^{-1})	HIIT vs Fartlek	+0.30	0.01 to 0.59	0.049
	Fartlek vs MCT	+1.10	0.70 to 1.50	<0.001
	HIIT vs MCT	+0.80	0.40 to 1.20	<0.001
Running Economy (↓ better)	HIIT vs Fartlek	−0.30	−0.63 to 0.03	0.062
	Fartlek vs MCT	−2.10	−2.80 to −1.40	<0.001
	HIIT vs MCT	−1.80	−2.50 to −1.10	<0.001
Stride Length (m)	HIIT vs Fartlek	+0.03	0.00 to 0.06	0.038
	Fartlek vs MCT	+0.07	0.04 to 0.10	<0.001
	HIIT vs MCT	+0.04	0.02 to 0.06	<0.001
Stride Frequency (steps·min^{-1})	HIIT vs Fartlek	+0.60	−0.05 to 1.25	0.071
	Fartlek vs MCT	+3.20	1.50 to 4.90	0.001
	HIIT vs MCT	+2.60	1.00 to 4.20	0.003
Ground Contact Time (ms; ↓better)	HIIT vs Fartlek	−1.90	−3.85 to 0.05	0.051
	Fartlek vs MCT	−9.10	−11.50 to −6.70	<0.001
	HIIT vs MCT	−7.20	−9.30 to −5.10	<0.001
HRR1 (bpm)	HIIT vs Fartlek	+0.50	−0.03 to 1.03	0.062
	Fartlek vs MCT	+3.90	2.60 to 5.20	<0.001
	HIIT vs MCT	+3.40	2.20 to 4.60	<0.001
HRR2 (bpm)	HIIT vs Fartlek	+0.20	−0.02 to 0.42	0.081
	Fartlek vs MCT	+3.50	2.30 to 4.70	<0.001
	HIIT vs MCT	+3.30	2.10 to 4.50	<0.001
HRR3 (bpm)	HIIT vs Fartlek	0.00	−0.42 to 0.42	0.998
	Fartlek vs MCT	+3.80	2.60 to 5.00	<0.001
	HIIT vs MCT	+3.80	2.60 to 5.00	<0.001

Table 6. One-Way ANOVA on Change Scores (Δ) Between Groups (Fartlek, High Intensity Interval Training (HIIT), MCT)

Variable	Between-three groups	df	MS	F	p-value	Partial η^2
VO_2max (ml·kg^{-1}·min^{-1})	214.2	2	107.10	45.6	<0.001	0.47
vVO_2max (km·h^{-1})	18.7	2	9.35	31.2	<0.001	0.38
Running Economy (VO_2 ml·kg^{-1}·min^{-1}; ↓better)	67.4	2	33.70	24.8	<0.001	0.35
Stride Length (m)	0.032	2	0.016	18.1	<0.001	0.27
Stride Frequency (steps·min^{-1})	245.6	2	122.8	6.2	0.003	0.11
Ground Contact Time (ms; ↓better)	8311.0	2	4155.5	39.4	<0.001	0.44
HRR1 (bpm)	329.4	2	164.7	32.7	<0.001	0.39
HRR2 (bpm)	446.1	2	223.0	34.9	<0.001	0.40
HRR3 (bpm)	386.8	2	193.4	28.5	<0.001	0.36

A similar pattern was observed for vVO_2max, where HIIT outperformed Fartlek with a modest yet significant difference (Δ = +0.30, p = 0.049), and both high-intensity modalities produced substantially higher improvements than MCT.

For running economy, although the difference between HIIT and Fartlek did not reach statistical significance (p = 0.062), both groups outperformed MCT with large effect magnitudes, reflected by lower oxygen cost at submaximal speeds. Stride length showed a significant advantage for HIIT over Fartlek (Δ = +0.03, p = 0.038), while both HIIT and Fartlek yielded greater stride length improvements than MCT. In terms of stride frequency, differences between HIIT and Fartlek were not statistically significant (p = 0.071), yet both modalities demonstrated superior adaptations compared with MCT (p ≤ 0.003).

Ground contact time (GCT) improved more prominently in both HIIT and Fartlek compared with MCT (p < 0.001), with the HIIT–Fartlek comparison approaching but not reaching significance (p = 0.051), suggesting comparable efficiency gains in lower-limb elastic utilization. For HRR1–HRR3, the differences between HIIT and Fartlek were non-significant across all indices (p = 0.062–0.998). Nevertheless, both HIIT and Fartlek displayed significantly greater parasympathetic reactivation following exercise when compared to MCT ($p < 0.001$), illustrating the clear superiority of high-intensity methods in enhancing autonomic recovery.

Taken together, the post-hoc findings indicate that HIIT and Fartlek consistently induce greater physiological and biomechanical adaptations than moderate continuous training. Although the two high-intensity modalities share many overlapping benefits, HIIT demonstrates a slight edge over Fartlek in several key performance indicators, particularly VO_2max, vVO_2max, and stride length, underscoring its efficacy as a potent stimulus for aerobic and neuromuscular enhancement.

The results of the one-way ANOVA test of nine performance variables showed significant differences between the three exercise groups ($p < 0.001$ for most variables). Consistently, the HIIT group showed the greatest improvement in physiological and biomechanical performance compared to the other two groups.

On the VO_2max variable, the HIIT group recorded the highest increase with very strong effects ($F = 45.6$, $p < 0.001$, partial $\eta^2 = 0.47$), suggesting that the HIIT intervention provided a much greater cardiorespiratory adaptation than the other two groups. A similar pattern was seen in vVO_2max ($F = 31.2$, $p < 0.001$, $\eta^2 = 0.38$), reinforcing that HIIT resulted in a superior increase in maximum aerobic speed capacity.

In terms of running economy, the HIIT group showed the most efficient reduction in VO_2 ($F = 24.8$, $p < 0.001$, $\eta^2 = 0.35$), which indicates more economical energy use at a given speed. Biomechanical components that support performance such as stride length ($F = 18.1$, $p < 0.001$, $\eta^2 = 0.27$) also increased the most in the HIIT group, while stride frequency also showed HIIT superiority even with moderate effects ($F = 6.2$, $p = 0.003$, $\eta^2 = 0.11$).

In the neuromuscular variables related to running efficiency, the HIIT group showed the greatest decrease in ground contact time ($F = 39.4$, $p < 0.001$, $\eta^2 = 0.44$), indicating better elasticity and mechanical efficiency than the other groups.

In addition, cardiovascular recovery ability measured through HRR1, HRR2, and HRR3 also showed that the HIIT group had the best acceleration of heart rate recovery (HRR1: $F = 32.7$, $p < 0.001$, $\eta^2 = 0.39$; HRR2: $F = 34.9$, $p < 0.001$, $\eta^2 = 0.40$; HRR3: $F = 28.5$, $p < 0.001$, $\eta^2 = 0.36$).

Overall, the pattern of findings across all variables suggests that the HIIT group produces the most comprehensive physiological, biomechanical, and cardiovascular adaptations, with large to very large effect size values on most key parameters. These findings suggest that HIIT demonstrates greater effectiveness relative to the other training modalities examined in this study in improving aerobic performance, running efficiency, and recovery ability.

Discussion

The findings of this study demonstrate that all three training modalities Fartlek, High-Intensity Interval Training (HIIT), and Moderate Continuous Training (MCT) produced significant improvements in physiological and biomechanical variables following eight weeks of intervention. However, HIIT consistently yielded the greatest magnitude of adaptation within the present sample, indicating a higher effectiveness for enhancing aerobic and biomechanical performance in this educational context. Physiologically, the marked improvement in VO_2max observed in the HIIT group reflects enhanced cardiovascular and respiratory capacity through increases in stroke volume, cardiac output, and skeletal muscle capillarization, coherent with established mechanisms of high-intensity exertion (Sopyan et al., 2023). The superior gains in vVO_2max also indicate improved metabolic efficiency and lactate tolerance, hallmarks of interval-based training that demands robust neuromuscular coordination. These improvements align with core mechanisms of interval training, particularly the repeated exposure to high-intensity bouts that generate substantial metabolic stress, stimulate mitochondrial biogenesis, and recruit both type I and type II fibers, thereby producing a broader adaptive signal than MCT or Fartlek (Atakan, Li, et al., 2021).

Although some previous studies have reported comparable improvements between MCT and HIIT, such as the original research conducted in runners populations by (Z. Wang & Wang, 2024), these findings are limited by heterogeneous protocols and small sample sizes. The present study addressed these limitations by employing a larger sample ($n = 102$) of healthy young adults and incorporating more comprehensive physiological and biomechanical assessments. As a result, the current findings offer stronger evidence that HIIT provides the most potent physiological stimulus within populations that are highly responsive to high-intensity workloads (Tian et al., 2023).

From a biomechanical perspective, the HIIT group exhibited the greatest enhancements. High-intensity accelerations likely facilitated enhanced motor-unit synchronization and improved elastic energy utilization. These adaptations reflect improved mechanical efficiency and neuromuscular performance elicited by repeated exposure to high-intensity accelerations (Gao et al., 2024; Preece et al., 2019). The reduction in ground contact time in the HIIT group indicates more efficient force application, consistent with research showing that shorter contact times are associated with reduced submaximal oxygen consumption. The reduction in ground contact time is particularly meaningful, as shorter contact reflects greater leg stiffness, faster force transmission, and reduced submaximal oxygen cost, all of which translate into more economical running patterns (Dolci et al., 2021; Penichet-Tomas, 2024). Such biomechanical optimization provides an additional performance advantage for HIIT beyond its physiological benefits (Gao et al., 2024; Jin et al., 2025).

Running economy improved across all groups but was most pronounced in the HIIT condition. The reduction in submaximal VO_2 during steady-state running indicates enhanced metabolic efficiency, aligning with evidence that high-intensity interval exposure induces superior energy utilization strategies and neuromuscular economy. Repeated recruitment of high-threshold motor units during HIIT likely increased oxidative capacity within type II fibers traditionally more glycolytic which improves energy turnover efficiency at lower intensities, explaining the superior running economy adaptations compared with Fartlek and MCT (Feng et al., 2025; Olaya-Cuartero, Lopez-Arbues, et al., 2024). Compared with Fartlek and MCT, the structured intensity profile of HIIT delivers stronger metabolic adaptation due to the repeated recruitment of large motor units and high oxidative demand (Tsai et al., 2021).

Cardiovascular recovery (HRR1–HRR3) improved in all groups; however, HIIT produced the largest enhancements, indicating faster parasympathetic reactivation following exertion. The accelerated heart-rate recovery indicates faster parasympathetic reactivation and reduced sympathetic persistence, suggesting more efficient autonomic regulation following high-intensity exertion (L. Wang et al., 2021). This accelerated recovery reflects improved autonomic balance and vagal responsiveness, which are critical for repeated high-intensity efforts (Wu et al., 2021). Enhanced HRR is especially relevant in athletic contexts, as it supports superior tolerance to successive training sessions and reduces accumulated fatigue (Zhao & Sim, 2023). The absolute changes and effect size estimates revealed that HIIT consistently produced the greatest adaptations. Although it is recognized that interval and continuous training may yield comparable benefits when matched for energy expenditure (Zanini et al., 2025), the metabolic oscillation and sympathetic parasympathetic cycling inherent to HIIT deliver an autonomic stimulus that continuous training does not replicate. The structured high-intensity demands of HIIT provide an additional stimulus that is not replicated by unstructured variability or continuous moderate intensity (W. Wang et al., 2025).

Large effect sizes were observed for key variables such as VO_2max ($\eta^2 = 0.47$), ground contact time ($\eta^2 = 0.44$), and HRR2 ($\eta^2 = 0.40$), indicating that the physiological and biomechanical adaptations were not only statistically significant but also practically meaningful. These outcomes strengthen the conclusion that HIIT elicits the most substantial training effects within a comparable intervention duration (Möhler et al., 2021). Such efficiency is particularly relevant for practitioners and athletes who require rapid adaptation within constrained training timeframes (Litleskare et al., 2020).

Although both MCT and Fartlek contributed to measurable improvements (Prasanna & Vaithianathan, 2019), their effect sizes tended to be moderate or small relative to HIIT (Arsadi et al., 2025a). Continuous training remains valuable for foundational endurance development, yet its lower metabolic stress and predominantly type I fiber recruitment produce slower adaptive rates (Engelbrecht et al., 2024). In contrast, HIIT training offers a more efficient and time-effective approach for achieving substantial improvements in aerobic and mechanical performance (Kelemen et al., 2023).

The superiority of HIIT can be attributed to its unique physiological mechanisms, which combine intensive aerobic and anaerobic stimulation (Feng et al., 2025). Increases in VO_2max and vVO_2max in the HIIT group reflect improved oxygen transport, mitochondrial efficiency, and elevated lactate threshold, consistent with the adaptive profile of high-intensity workloads (Xie et al., 2024). Concurrent activation of type I and type II muscle fibers during HIIT supports stronger neuromuscular adaptation, enhancing mechanical and metabolic efficiency (Costache et al., 2024). The present findings are aligned with literature demonstrating accelerated aerobic and mechanical gains from high-intensity interval training in young adults (Ai et al., 2021). Variability in previous studies largely reflects differences in participant characteristics, intervention duration, and measurement protocols. By incorporating a comprehensive set of physiological and biomechanical assessments, the present study offers a more holistic representation of training adaptations.

Some studies report minimal differences between HIIT and continuous training when interventions are brief or matched strictly by volume (Atakan, Güzel, et al., 2021). However, these studies often neglect biomechanical metrics and recovery indices. The current findings bridge this gap by including stride length, ground contact time, and HRR, providing a more complete understanding of training-induced adaptations.

Biomechanical improvements such as greater stride length and reduced contact time in the HIIT group suggest that this protocol not only enhances aerobic capacity but also optimizes mechanical running efficiency (Olaya-Cuartero, Pueo, et al., 2024). Although Fartlek produced notable improvements (Arsadi et al., 2025), the structured nature of HIIT resulted in more targeted neuromuscular adaptation (Cáceres-Diego et al., 2025). This supports theoretical models proposing that structured high-intensity intervals are superior to unstructured variable-intensity running for improving mechanical efficiency (Shingala & Shukla, 2024).

Stride frequency improved moderately in both HIIT and Fartlek, with minimal changes in MCT. The balance between stride frequency and stride length is essential for optimal running performance. Improvements in stride frequency across HIIT and Fartlek further demonstrate refined motor control and rhythm regulation, which are essential for efficient running mechanics (Llanos-Lagos et al., 2024). These findings further reinforce the superiority of HIIT in integrating neuromuscular and technical adaptations (Strepp et al., 2024). Running economy improved most significantly in the HIIT group. The superior running economy observed in the HIIT group is consistent with evidence that interval training enhances intermuscular coordination, reduces co-contraction, and improves energy-conserving movement patterns, contributing to a lower oxygen cost during submaximal effort (Dolci et al., 2021; Feng et al., 2025). Prior studies highlight that high-intensity intervals promote enhanced motor efficiency and energy conservation (Zanini et al., 2025), aligning with the robust improvements observed in this study.

The faster parasympathetic recovery demonstrated by HRR1 to HRR3 in the HIIT group suggests superior autonomic regulation, linked to enhanced vagal reactivation and reduced sympathetic drive. Additionally, greater parasympathetic rebound and reduced sympathetic strain following HIIT likely contribute to better overall load management and reduced neuromuscular fatigue (Moro et al., 2020). This adaptation is critical for maintaining performance capacity and reducing fatigue during successive high-intensity sessions (D'Alleva et al., 2023). Although external variables such as nutrition, sleep, and unmonitored physical activity were difficult to control despite standardized instructions, the randomized controlled design and comprehensive measurements enhanced the robustness of these findings. The sample was limited to healthy young adults, and caution is warranted when generalizing findings to older or elite populations.

Overall, the results clearly indicate that HIIT showed the most pronounced improvements in physiological and biomechanical performance among the training protocols examined in this cohort of young adult students. Its combination of high metabolic stress, broad motor-unit recruitment, enhanced mitochondrial and neuromuscular adaptation, and superior autonomic recovery explains its superiority over Fartlek and MCT. Variability in previous studies is largely explained by differences in sample and protocol characteristics, whereas the present findings provide coherent and comprehensive evidence of HIIT's superiority. Collectively, the study highlights the importance of integrating physiological and biomechanical adaptations within high-intensity training (Gao et al., 2024; L. Wang et al., 2021; Z. Wang & Wang, 2024). HIIT not only enhances aerobic capacity but also optimizes stride mechanics and ground contact variables, producing highly efficient running patterns (Dolci et al., 2021; Gao et al., 2024a). These findings provide practical implications for coaches and practitioners to design time-efficient, high-impact training programs.

Future research should explore the effects of HIIT in competitive athletes, youth populations, and individuals with metabolic conditions. Further studies integrating physiological, biomechanical, and psychological markers such as lactate tolerance, neuromuscular activation, and mental fatigue are warranted. Investigations into optimal interval structures could also refine HIIT protocols for maximizing performance while minimizing injury risk.

Conclusion

The present study provides clear evidence that Fartlek, High-Intensity Interval Training (HIIT), and Moderate Continuous Training (MCT) all contribute to measurable improvements in aerobic performance, running mechanics, and cardiovascular recovery in young adult learners. Among these modalities, HIIT produced the most substantial and multidimensional adaptations, particularly in VO_2max, vVO_2max, stride mechanics, running economy, and HRR indices. These outcomes highlight the potent physiological and neuromuscular stimulus generated by structured high-intensity interval workloads.

From an educational and practical standpoint, the findings emphasize that HIIT represents a highly time-efficient and impactful training option for physical education settings. The structured intervals, clear intensity targets, and strong physiological returns make HIIT suitable for course-based conditioning programs, especially when instructional time is limited. Educators and coaches may use these results to design evidence-based training prescriptions that enhance both fitness and technical running proficiency among students.

Despite its strengths, this study is subject to several limitations. External factors such as sleep, nutritional intake, and unmonitored physical activity could not be fully standardized, potentially influencing training responses. The sample healthy, physically active young adults also limits generalizability to elite athletes, youth, or older populations. Additionally, the study did not include advanced physiological markers such as lactate thresholds, muscle activation patterns, or hormonal responses, which may offer deeper mechanistic insights. Future investigations should expand to diverse populations and athletic levels, incorporate longer intervention durations, and integrate more advanced physiological and biomechanical assessments. Comparisons of different HIIT structures (e.g., work-to-rest ratios, interval duration, and intensity progression) and dose–response analyses will be critical for optimizing training strategies in both educational and sport performance contexts.

Data Availability Statement

The data supporting the findings of this study are not publicly available due to ethical restrictions related to participant privacy and confidentiality. Anonymized or aggregated datasets may be made available by the corresponding author upon reasonable request and subject to institutional and ethical approval.

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Conflicts of Interest

The authors declare no conflict of interest.

AI Transparency Statement

The authors declare that no generative artificial intelligence (AI) tools were used in the collection, analysis, or interpretation of the study data. AI-assisted software (Grammarly) was employed solely for language editing and grammar refinement during manuscript preparation.

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Високоінтенсивне інтервальне тренування перевершує фартлек і метод безперервного тренування за аеробними та біомеханічними адаптаціями бігу: Дані в контексті легкоатлетичної освіти

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

Реферат. Стаття: 13 с., 6 табл., 1 рис., 47 джерел.

Обґрунтування. Аеробна здатність та біомеханічна ефективність є ключовими детермінантами результативності в легкій атлетиці. Проте емпіричні дані, що безпосередньо порівнюють різні модальності тренувань за допомогою комплексної оцінки фізіологічних, біомеханічних та кардіоваскулярних показників відновлення, залишаються обмеженими, особливо в межах структурованого навчально-тренувального процесу з легкої атлетики.

Цілі. Метою цього дослідження було порівняти ефективність фартлеку, методів високоінтенсивного інтервального тренування (ВІІТ) та помірного безперервного тренування (ПБТ) щодо впливу на аеробну здатність, ефективність бігу та відновлення серцево-судинної системи у студентів спортивних спеціальностей, які відвідують курси з легкої атлетики, тим самим забезпечуючи нове розуміння доказово обґрунтованих стратегій кондиційної підготовки, актуальних для тренувального процесу в легкій атлетиці.

Матеріали та методи. Загалом 102 студенти спортивних спеціальностей, які проходили курс легкої атлетики, було розподілено за методом рандомізації на групи ВІІТ (n = 34), фартлеку (n = 34) або ПБТ (n = 34). Тривалість інтервенції становила 8 тижнів і складалася з трьох тренувальних сесій на тиждень. Вимірювані показники результативності включали VO_2max (максимальне споживання кисню), vVO_2max (швидкість, що відповідає VO_2max), економічність бігу, механіку кроку та відновлення серцевого ритму (HRR1–HRR3). Дані аналізували за допомогою t-критеріїв для парних вибірок, однофакторного дисперсійного аналізу, post hoc тестів найменшої значущої різниці та розрахунків величини ефекту (d Коена; часткова η^2).

Результати. Усі тренувальні моделі продемонстрували статистично значуще покращення за всіма параметрами ($p < 0.001$). Використання методу високоінтенсивного інтервального тренування забезпечило найбільш суттєвий приріст показників VO_2max, vVO_2max, економічності бігу, довжини кроку, часу контакту з поверхнею та індексів відновлення серцевого ритму. Дисперсійний аналіз виявив значущі міжгрупові відмінності за всіма основними змінними ($p < 0.001$; $\eta^2 = 0.27–0.47$), що свідчить про вищу адаптаційну відповідь організму на ВІІТ порівняно з фартлеком та помірним безперервним тренуванням у контексті легкоатлетичної підготовки.

Висновки. Результати підтверджують, що серед досліджуваних методів тренування саме ВІІТ продемонструвало найбільше покращення показників аеробної здатності, механічної ефективності бігу та відновлення серцево-судинної системи у даної когорти студентів спортивних спеціальностей. Перевага зазначеного методу зумовлена структурованими високоінтенсивними стимулами, що максимально активізують серцево-судинну систему, мітохондріальну адаптацію, лактатну толерантність та рекрутування нервово-м'язових одиниць. Подальші дослідження мають бути спрямовані на вивчення реакцій у професійних атлетів, збільшення тривалості інтервенції та впровадження поглибленого метаболічного й нервово-м'язового аналізу для кращого розуміння адаптаційних процесів, зумовлених ВІІТ у легкій атлетиці.

Ключові слова: тренування з фартлеку, високоінтенсивне інтервальне тренування (ВІІТ), тренування з легкої атлетики, аеробна здатність, економічність бігу, механіка кроку, відновлення серцево-судинної системи, VO_2max.

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