QUBAHAN JOURNAL OF COACHING AND SPORTS SCIENCES
VOL. 2, NO. 3, August 2024
https://doi.org/10.48161/qcsj.v2n3a26

Effects of High-Intensity Interval Training on Running Economy, Lactate Threshold, and Time-to-Exhaustion in Trained Distance Runners

Emeka Mong [1]*, Aderonmu Kehinde Adebayo[2], and Jonathan V. Pagdato[3]

[1] Human Kinetics and Health Education, Ebonyi State University, Abakaliki, Nigeria;
[2] Kinesiology, Health Education, and Recreation, Faculty of Education, Obafemi Awolowo University, Ile-Ife, Nigeria;
[3] College of Arts and Social Science, Mindanao State University, Marawi City, Philippines.

* **Corresponding author: fathermong2012@gmail.com.**

ABSTRACT: This study examined whether replacing a modest portion of habitual endurance running with structured high-intensity interval training (HIIT) improves running economy, lactate-threshold velocity, and time-to-exhaustion in trained male distance runners. Twenty-eight trained male runners were randomized to HIIT (n = 14) or to a control group (n = 14) for 8 weeks. The HIIT group completed two supervised weekly sessions, progressing from 4 x 3 min to 6 x 3 min at 90-95% of VO2max velocity, separated by 2-min active recoveries, while reducing easy mileage to keep weekly training time comparable with the control group. The control group maintained habitual endurance training. Running economy at 12 and 14 km/h, blood lactate during submaximal running, velocity at 4 mmol·L-1 blood lactate, VO_2max, velocity at VO_2max, time-to-exhaustion at velocity at VO_2max, and 5-km time-trial performance were measured before and after training. Group-by-time effects were assessed using mixed repeated-measures analysis of variance, with significance set at $p < 0.05$. HIIT produced greater improvements than control in running economy at 14 km/h (-3.8% vs -0.6%, $p < 0.001$), velocity at 4 mmol·L-1 lactate (+4.2% vs +1.1%, $p < 0.001$), time-to-exhaustion (+15.8% vs +2.8%, $p < 0.001$), and 5-km time-trial time (-2.6% vs -0.6%, $p = 0.002$). VO2max improved modestly after HIIT (+2.6% vs +0.8%, $p = 0.027$). A carefully dosed HIIT substitution block improved linked determinants of endurance performance without increasing total weekly training time. The findings support HIIT as a targeted redistribution strategy in trained male runners rather than as an indiscriminate addition of hard training.

Keywords: high-intensity interval training; running economy; lactate threshold; VO2max; time-to-exhaustion; trained male runners; endurance performance.

I. INTRODUCTION

A narrow but important set of physiological abilities shapes distance-running performance. Athletes must possess a high maximal aerobic capacity. Still, they must also use that capacity economically and sustain a large fraction of it before lactate accumulation becomes destabilizing. Classic work in trained runners demonstrated that running economy helps explain meaningful variation in performance even among athletes with similar competitive ability [1]. Later reviews consolidated this view by showing that the oxygen cost of running, the speed associated with the lactate threshold, and maximal oxygen uptake interact rather than act as isolated predictors [2], [3]. This is especially relevant for trained runners, whose VO_2max may already be well developed and whose remaining improvements often depend on smaller changes in efficiency, pacing tolerance, and metabolic stability.

A runner who uses less oxygen at a fixed speed can cover the same distance with a lower cardiometabolic cost, preserve a larger reserve for later stages of a race, and tolerate demanding workouts with less accumulated strain. Coaches often describe this improvement as a pace beginning to feel smoother or more controllable. From a physiological perspective, economy reflects the combined influence of muscle-tendon behavior, coordination, substrate use, ventilation, and the energetic cost of stabilizing the body during repeated strides. Because trained runners already complete high volumes of specific practice, improvements in economy are usually modest; however, even a 2-4% reduction in oxygen cost may be practically important when the athlete competes over 3000 m to 10 km.

The lactate threshold provides a complementary marker because it describes how fast a runner can move before blood lactate rises rapidly or reaches a predefined concentration. Threshold concepts must be interpreted carefully because fixed lactate values, lactate turn points, maximal lactate steady state, and ventilatory thresholds are not identical [4], [5]. Nevertheless, threshold-related running speed remains useful in applied sport science. If an athlete can run faster at the same lactate concentration after training, the same race or tempo speed usually represents a lower internal load. For distance runners, this shift can improve the quality of threshold sessions and reduce the cost of pace changes during competition.

Time-to-exhaustion at the velocity associated with VO2max provides another perspective. It is a severe-intensity test rather than a direct race result. Still, it captures how long a runner can sustain high oxygen demand, elevated ventilation, metabolic disturbance, and neuromuscular fatigue at a speed close to the athlete's upper aerobic range [6]. This outcome is useful because runners do not win races based solely on VO2max. They must maintain posture and rhythm while fatigue accumulates, and they must resist the progressive loss of efficiency that occurs when stride mechanics become less economical. A training intervention that improves economy and threshold speed would reasonably be expected to increase time-to-exhaustion as well.

High-intensity interval training has long been used in endurance sports because it allows athletes to accumulate time at high percentages of VO2max without requiring continuous maximal effort [7], [8]. However, the label HIIT covers many different prescriptions. A session of 30-s repetitions, a set of 3-min repetitions, and a workout of long intervals at 90-95% of VO2max velocity are not the same stimulus. The duration of each repetition, the intensity, the recovery mode, the weekly frequency, and the placement in the training week influence whether the main response is cardiovascular, metabolic, neuromuscular, or simply excessive fatigue. This distinction is important for trained runners, who often have little tolerance for adding more hard work on top of an already demanding program.

Running-specific studies suggest that interval training can improve several performance determinants, but the magnitude and direction of change vary by population and training design. Interventions using high-intensity aerobic intervals have reported improvements in VO2max, velocity at VO2max, time-to-exhaustion, and some submaximal markers [9], [10]. Other work has shown that the economy can also respond to training methods that modify neuromuscular demand, such as plyometric or strength-oriented programs. Taken together, these findings suggest that a well-designed HIIT program may improve performance through multiple pathways rather than through a single maximal aerobic mechanism.

The present study addressed this issue by examining an 8-week HIIT substitution intervention in trained male distance runners. The program used two weekly sessions of 3-min repetitions at 90-95% of VO2max velocity, with active recovery and a gradual progression from four to six repetitions. This prescription was chosen because it is intense enough to challenge aerobic power and high-speed coordination, but not so severe that it becomes an all-out sprint program. The primary outcomes were running economy at 14 km/h, blood lactate at 4 mmol·L-1, and time-to-exhaustion at VO2max velocity. Secondary outcomes included running economy at 12 km/h, blood lactate at 14 km/h, VO2max, velocity at VO2max, and 5-km time-trial performance. The central question was whether a controlled redistribution of training intensity would improve the physiological traits linked to performance that matter most to trained distance runners.

1. *AIMS AND HYPOTHESES*

The aims of the study were:

- To determine whether an 8-week HIIT substitution program improves running economy at submaximal speeds in trained male distance runners.
- To examine whether HIIT improves velocity at 4 mmol·L-1 blood lactate and reduces blood lactate at a fixed submaximal speed.

- To evaluate whether HIIT increases VO2max, velocity at VO2max, and time-to-exhaustion at velocity at VO2max.
- To examine whether changes in running economy and threshold-related speed are associated with changes in time-to-exhaustion.

The hypotheses were:

- HIIT would produce a greater reduction in oxygen cost at 14 km/h than habitual endurance training.
- HIIT would produce a greater increase in velocity at 4 mmol·L-1 blood lactate and a greater reduction in blood lactate at 14 km/h than control training.
- HIIT would increase time-to-exhaustion at velocity at VO2max more than control training, with a smaller but meaningful improvement in VO2max.
- Runners with larger improvements in running economy and lactate-threshold velocity would show larger improvements in time-to-exhaustion.

II. LITERATURE REVIEW

Running economy has remained central to endurance physiology because it translates laboratory oxygen uptake into the practical language of running speed. Fletcher and colleagues argued that the economy should be interpreted beyond the simple measurement of oxygen uptake because the same value can arise from different combinations of mechanical and metabolic behavior [11]. Foster and Lucia described the economy as a neglected factor in elite performance, partly because maximal oxygen uptake attracts more attention, even though economy better explains differences among already well-trained athletes [12]. These perspectives are important for the present study because HIIT may improve economy through several routes. Repeated running at high but controlled speeds can sharpen stride rhythm, increase exposure to race-relevant mechanics, and improve the ability to direct force efficiently. A reduction in oxygen cost after HIIT, therefore, does not need to be attributed to one isolated mechanism; it may reflect a combined improvement in neuromuscular coordination, elastic energy use, and metabolic control.

Jones and Carter summarized how training can influence VO2max, exercise economy, lactate threshold, and oxygen-uptake kinetics, showing that the response to endurance work is broad rather than confined to a single marker [13]. Midgley and colleagues later emphasized that training programs for runners should target multiple determinants simultaneously because long-distance performance is rarely limited by a single factor [14]. A HIIT program that improves VO2max but worsens economy or leaves threshold unchanged would have a different value from a program that shifts all three traits in a favorable direction.

Stoa and colleagues showed that velocity at lactate threshold is influenced by performance level and by the combination of aerobic capacity and economy [15]. The threshold provides a useful way to describe the transition from manageable metabolic stress to progressively unstable exercise. When a runner can complete the same submaximal speed with lower blood lactate or run faster at a fixed lactate concentration, the training adaptation is visible in both the laboratory and the workout environment. This makes threshold-related outcomes particularly useful in trained runners who already complete substantial low-intensity mileage.

Buchheit and Laursen presented high-intensity interval training as a set of interacting programming decisions: work-bout duration, recovery intensity, recovery duration, accumulated work time, and exercise mode all change the physiological response [16], [17]. In distance running, a 3-min interval at 90-95% of VO2max is long enough to substantially increase oxygen uptake. Still, it remains short enough to preserve mechanics and reduce the likelihood that the athlete turns the session into a race. Active recovery also maintains aerobic demand and more closely resembles normal running practice than standing recovery.

Several runner-specific intervention studies support the use of interval training, although their prescriptions and outcomes vary. Smith and colleagues used velocity at VO2max and time at velocity at VO2max to individualize training and reported improvements in performance-related variables [18]. Denadai and colleagues compared interval training at 95% and 100% of VO2max velocity and showed that high-intensity running can influence aerobic physiological indices and running performance in well-trained runners [19]. Seiler and colleagues demonstrated that, in trained endurance athletes, interval duration and total work time interact to shape adaptation [20]. These studies collectively support the idea that the interval format and total work prescription should be matched to the intended adaptation.

Ferley and colleagues reported that both uphill and level-grade high-intensity interval training could improve variables such as VO2max, maximal velocity, lactate-threshold velocity, and time-to-exhaustion in well-trained distance runners [21]. A related study showed that incline and level-grade HIIT influenced running-economy components and muscle-power outcomes, although not all variables improved equally [22]. These results are useful because they show that HIIT effects extend beyond central oxygen delivery. velocity, muscular demand, and specificity all contribute to how a runner responds. The present study used level running to keep the intervention directly relevant to flat road or track racing while avoiding the added muscular specificity of uphill work.

Iaia and colleagues reported that a period of speed-endurance training reduced energy expenditure during exercise while maintaining muscle oxidative capacity despite a reduction in training volume [23]. This finding is important because it challenges the assumption that reducing low-intensity volume necessarily weakens aerobic capacity. When intensity is carefully redistributed, total volume can be lower or stable while key performance markers improve. The present study followed a similar practical principle by reducing some easy mileage in the HIIT group so that the intervention represented a substitution rather than a simple increase in workload.

Milanovic and colleagues found that high-intensity interval training and continuous endurance training can both improve VO2max, with larger gains often observed after interval training in healthy adults [24]. However, trained runners are not the same as sedentary or recreational samples. Their baseline adaptation is higher, their weekly training is more stable, and the margin for improvement is smaller. A modest increase in VO2max may therefore be meaningful only when interpreted alongside improvements in economy, threshold velocity, and time-to-exhaustion. This is why the present analysis reports both maximal and submaximal outcomes.

Neuromuscular training studies provide another context for interpreting changes in economy. Saunders and colleagues showed that short-term plyometric training improved running economy in highly trained middle- and long-distance runners [25]. Paavolainen and colleagues reported that explosive-strength training improved 5-km running time partly through improved running economy and muscle power [26]. Storen and colleagues showed that maximal strength training improved running economy in distance runners without necessarily changing VO2max [27]. These findings demonstrate that the economy can improve through mechanisms that are not purely cardiovascular in nature. HIIT may share some of this neuromuscular pathway because repeated fast running requires better force timing, posture control, and elastic return than easy running.

Esteve-Lanao and colleagues found that performance in endurance athletes was influenced by the relative contribution of time spent below versus near threshold [28]. Seiler and Kjerland described the intensity distribution of elite endurance athletes and reported that a large proportion of training is often completed below the first threshold [29]. Seiler later argued that successful endurance programming usually combines high volumes of low-intensity training with carefully placed high-intensity work [30]. These observations do not argue against HIIT. Instead, they suggest that HIIT should be implemented carefully and in limited doses. The present intervention followed this view by using two weekly sessions while preserving the long run and several easy runs.

Foster and colleagues introduced the session-RPE approach as a practical way to quantify internal training load across different workout types [31]. Hopkins emphasized the need to interpret change alongside measurement reliability, especially when sample sizes are limited, and outcomes may vary from day to day [32]. These ideas guided the present study's focus on adherence, adverse events, and effect sizes, in addition to p-values. A statistically significant difference is more useful when the direction, magnitude, and practical meaning of the change are all clear.

III. MATERIALS AND METHODS

1. *STUDY DESIGN*

A parallel-group randomized controlled design was used. Trained male distance runners completed baseline testing, were randomized to HIIT or control training, and repeated the same testing battery after 8 weeks. Randomization was stratified by recent 5-km performance to reduce baseline imbalance in competitive level. All testing took place in the same laboratory, and each runner was tested at the same time of day before and after the intervention. Participants were instructed to avoid strenuous training for 24 h, caffeine for 6 h, and food for 2 h before each test visit. The study was designed as a training-substitution intervention rather than an additional-load intervention.

2. *PARTICIPANTS*

Twenty-eight trained male distance runners completed the study. Inclusion criteria were age 18-35 years, at least three years of structured endurance training, current weekly running volume between 45 and 90 km, and recent competition or time-trial experience over 3000 m to 10 km. Exclusion criteria were musculoskeletal injury within the preceding three months, cardiometabolic disease, current medication known to affect exercise response, and altitude training or heat-acclimation camps during the intervention. All participants provided written informed consent. The institutional research ethics committee approved the protocol.

3. *TRAINING-HISTORY CHARACTERIZATION*

Participants completed a 4-week training-history log before baseline testing. The log recorded weekly distance, training time, number of sessions, hard workouts, long-run duration, perceived exertion for key sessions, and recent race results. These records confirmed that the sample consisted of trained runners with stable training routines rather than athletes returning from injury or beginning a new program. Most participants reported four to six weekly runs, one threshold-oriented or fartlek workout, and one longer run. Baseline training characteristics were similar across groups, supporting the interpretation that post-intervention differences reflected a redistribution of intensity rather than pre-existing training differences.

4. *INTERVENTION*

The HIIT group completed two supervised interval sessions each week. Sessions progressed from 4 x 3 min at 90-95% of velocity at VO2max in weeks 1-2, to 5 x 3 min in weeks 3-4, and to 6 x 3 min in weeks 5-8. Each repetition was separated by 2 min of easy running at approximately 55-60% of VO2max velocity. Every session began with 15 min of easy running, drills, and four progressive strides, and ended with 10 min of easy running. The HIIT group reduced low-intensity mileage enough to keep weekly training time close to baseline and comparable to that of the control group. The control group maintained habitual endurance training and did not add investigator-prescribed HIIT.

5. *TESTING PROCEDURES*

Testing was completed over two visits separated by 48-72 h. Visit 1 assessed running economy and lactate response during submaximal treadmill running. After a standardized warm-up, participants completed 4-min stages at 12, 13, 14, 15, 16, and 17 km · h-1, or until blood lactate exceeded 8 mmol·L-1 or the athlete could not safely continue. Oxygen uptake was averaged over the final minute of each stage. Capillary blood lactate was sampled immediately after each stage using a calibrated portable analyzer. Running economy was expressed as oxygen cost per kilometer relative to body mass. Velocity at 4 mmol·L-1 blood lactate was estimated by linear interpolation between adjacent stages.

6. *MAXIMAL AND PERFORMANCE TESTING*

Visit 2 included an incremental treadmill test to determine VO2max and velocity at VO2max. The test began at a comfortable running speed and increased by 1 km/h every minute until volitional exhaustion. VO2max was accepted when a plateau in oxygen uptake was observed or when at least two secondary criteria were present: respiratory exchange ratio above 1.10, heart rate within 5 beats·min-1 of age-predicted maximum, and rating of perceived exertion above 18 on the Borg 6-20 scale. After 20 min of standardized recovery, participants completed a constant-speed time-to-exhaustion test at a velocity corresponding to VO2max. A 5-km track time trial was completed within one week of laboratory testing under similar conditions before and after the intervention.

7. *OUTCOME MEASURES*

The prespecified primary outcomes were running economy at 14 km/h, blood lactate at 4 mmol·L-1, and time-to-exhaustion at velocity at VO2max. Secondary outcomes were running economy at 12 km/h, blood lactate concentration after the 14-km/h stage, VO2max, velocity at VO2max, 5-km time-trial performance, and heart rate at lactate threshold. Training adherence was calculated as the number of completed prescribed sessions divided by the planned sessions. Adverse events were recorded prospectively and classified as musculoskeletal, illness-related, or other.

8. STATISTICAL ANALYSIS

Data were screened using Shapiro-Wilk tests, visual inspection of Q-Q plots, and Levene tests for equality of variance. Descriptive statistics are presented as mean ± SD. Group-by-time effects were tested using a two-way mixed repeated-measures analysis of variance, with group as the between-participants factor and time as the within-participants factor. Where an interaction was detected, change scores were examined using independent-samples t-tests and Bonferroni-adjusted post hoc tests. Partial eta squared was reported for group-by-time effects, and Hedges g was reported for between-group change contrasts. Pearson correlations examined associations between changes in primary outcomes within the HIIT group. Statistical significance was set at $p < 0.05$.

IV. DATA ANALYSIS

All 28 runners completed the intervention and the post-test battery. No participant withdrew, and no cardiovascular adverse event occurred. One runner in the HIIT group reported mild calf tightness in week 3 and completed a reduced warm-up for one session, but no training days were lost. Adherence was high in both groups. The HIIT group completed 95.4% of prescribed interval sessions, and the control group completed 93.1% of planned habitual sessions. Weekly training time did not differ meaningfully between groups during the intervention, confirming that the HIIT prescription functioned as a redistribution of training intensity rather than as a larger total training dose.

Table 1 shows the baseline characteristics of the randomized groups. The groups were similar in age, stature, body mass, training history, weekly training volume, VO2max, velocity at VO2max, and recent 5-km performance. The small between-group differences were within the expected variation for trained club- and university-level male distance runners and did not suggest a systematic baseline advantage. This table is important because the interpretation of the intervention depends on the groups having comparable physiological and training backgrounds.

Table 1. Baseline characteristics of trained male distance runners.

Characteristic	**HIIT (n = 14)**	**Control (n = 14)**	**p value**
Age (years)	24.2 ± 3.7	24.6 ± 3.9	0.781
Stature (cm)	176.9 ± 5.8	177.4 ± 6.1	0.824
Body mass (kg)	67.2 ± 5.6	67.8 ± 5.9	0.786
Training history (years)	6.1 ± 2.3	6.0 ± 2.5	0.910
Weekly running volume (km·week-1)	66.8 ± 9.7	65.9 ± 10.2	0.813
Baseline VO$_2$max (mL·kg-1·min-1)	64.7 ± 4.7	64.5 ± 4.8	0.912
Baseline vVO$_2$max (km·h-1)	19.25 ± 0.75	19.23 ± 0.73	0.943
Baseline 5-km time trial (s)	1052 ± 64	1055 ± 65	0.903

Values are mean ± SD. HIIT = high-intensity interval training; vVO2max = velocity at VO2max. Independent-samples t tests confirmed no meaningful baseline differences between groups.

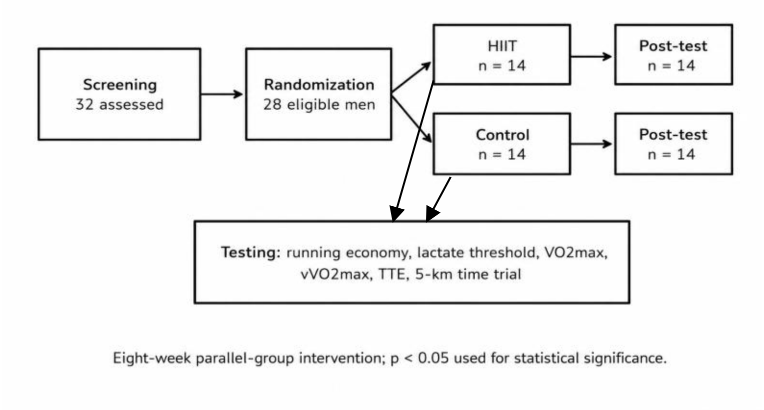
Table 2 summarizes training exposure during the intervention. The HIIT group completed the planned progression from 4 to 6 3-min repetitions, while total weekly training time remained similar to that of the control group. Session RPE was higher during HIIT sessions than during the control group's usual quality sessions, as expected. Still, the reduced easy mileage prevented a meaningful increase in total weekly time.

Figure 1 illustrates the study flow and confirms that all randomized participants were included in the final analysis. Figure 2 shows the intervention progression and the stable weekly training-time pattern across the 8 weeks.

Table 2. Intervention adherence and weekly training exposure.

Variable	HIIT	Control	p value
Planned weekly sessions	6.0 ± 0.4	5.8 ± 0.5	0.268
Completed weekly sessions	5.7 ± 0.5	5.4 ± 0.6	0.167
Training adherence (%)	95.4 ± 4.8	93.1 ± 5.6	0.252
Weekly training time (min·week-1)	401 ± 39	396 ± 45	0.771
Weekly running distance (km·week-1)	63.2 ± 8.8	65.1 ± 9.7	0.591
Weekly high-intensity sessions	2.0 ± 0.0	0.3 ± 0.4	<0.001
Mean HIIT/session RPE (CR-10)	7.2 ± 0.8	5.9 ± 0.9	<0.001
Adverse events requiring missed training	0	0	--

Values are mean ± SD. Session RPE values compare supervised HIIT sessions with the control group's usual quality sessions. The groups maintained similar total weekly training time.



Eight-week parallel-group intervention; p < 0.05 used for statistical significance.

FIGURE 1. Study flow and testing structure. The figure shows screening, randomization, completion, and the primary testing battery used before and after the 8-week intervention.

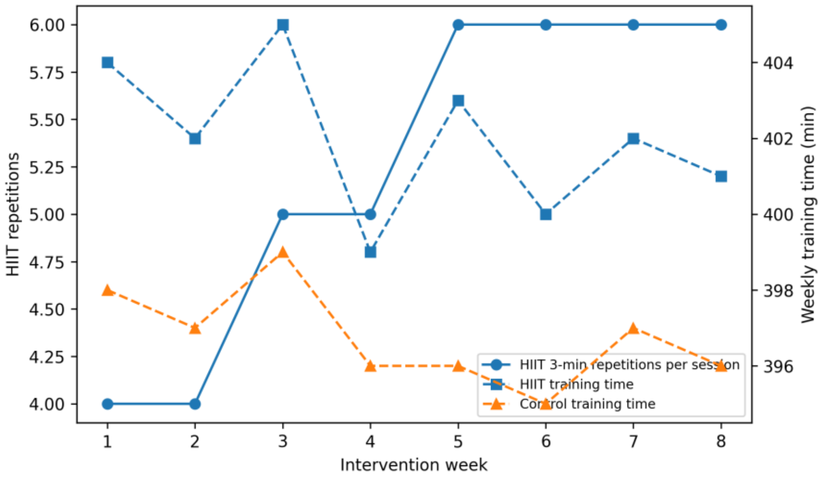


FIGURE 2. HIIT progression and weekly training-time stability. The HIIT group progressed from 4 to 6 3-min repetitions per session, while total weekly training time remained comparable to control.

The main physiological and performance outcomes are reported in Table 3. Significant group-by-time interactions were observed for running economy at 12 km/h and 14 km/h, blood lactate after the 14 km/h stage, velocity at 4 mmol·L-1 lactate, VO2max, velocity at VO2max, time-to-exhaustion, 5-km time-trial time, and heart rate at lactate threshold. The strongest effects were observed for running economy at 14 km/h, velocity at 4 mmol·L-1 lactate, velocity at VO2max, and time-to-exhaustion. Table 4 presents the inferential summary and shows that all primary outcomes were statistically significant at $p < 0.05$.

Table 3. Main physiological and performance outcomes before and after the 8-week intervention.

Outcome	Unit	HIIT Pre	HIIT Post	Control Pre	Control Post	Group x time p	Hedges g
Running economy at 12 km/h	mL·kg-1·km-1	203.1 ± 8.4	198.0 ± 8.7	202.6 ± 8.0	201.3 ± 8.4	0.004	-1.17
Running economy at 14 km/h	mL·kg-1·km-1	209.4 ± 9.1	201.5 ± 10.4	208.8 ± 8.7	207.5 ± 8.7	<0.001	-1.74
Blood lactate after a 14 km/h stage	mmol·L-1	3.74 ± 0.58	3.19 ± 0.70	3.71 ± 0.55	3.61 ± 0.66	<0.001	-1.39
Velocity at 4 mmol·L-1 lactate	km·h-1	15.46 ± 0.66	16.11 ± 0.74	15.42 ± 0.68	15.59 ± 0.79	<0.001	1.65
VO$_2$max	mL·kg-1·min-1	64.7 ± 4.7	66.4 ± 4.9	64.5 ± 4.8	65.0 ± 4.9	0.027	0.86
Velocity at VO$_2$max	km·h-1	19.25 ± 0.75	19.63 ± 0.87	19.23 ± 0.73	19.31 ± 0.69	<0.001	1.37
Time-to-exhaustion at vVO$_2$max	s	361 ± 52	418 ± 52	358 ± 49	368 ± 52	<0.001	1.52
5-km time trial	s	1052 ± 64	1025 ± 63	1055 ± 65	1049 ± 69	0.002	-1.23
Heart rate at lactate threshold	beats·min-1	168 ± 7	165 ± 7	168 ± 8	167 ± 8	0.014	-0.97

Values are mean ± SD. Lower values indicate improvement for running economy, blood lactate, 5-km time-trial time, and heart rate at lactate threshold. Hedges g represents the standardized between-group change contrast; the sign reflects the raw change direction, whereas the magnitude indicates the size of the between-group contrast.

Table 4. Mixed repeated-measures ANOVA summary for group-by-time effects.

Outcome	Mean change difference (HIIT - Control)	F(1,26)	p value	Partial eta squared
Running economy at 12 km/h	-3.80	10.12	0.004	0.28
Running economy at 14 km/h	-6.60	22.54	<0.001	0.46
Blood lactate after a 14 km/h stage	-0.45	14.25	<0.001	0.35
Velocity at 4 mmol·L-1 lactate	0.48	20.16	<0.001	0.44
VO$_2$max	1.20	5.46	0.027	0.17
Velocity at VO$_2$max	0.30	14.00	<0.001	0.35

Time-to-exhaustion at vVO₂max	47.00	17.17	<0.001	0.40
5-km time trial	-21.00	11.25	0.002	0.30
Heart rate at lactate threshold	-2.20	6.94	0.014	0.21

F values correspond to the group-by-time interaction for the 2 x 2 mixed design. Statistical significance was set at $p < 0.05$.

Figure 3 shows the pre-post pattern for running economy at 14 km/h. The HIIT group demonstrated a clear reduction in oxygen cost, whereas the control group showed only slight changes. This pattern supports the first hypothesis and indicates that repeated high-intensity running improved submaximal efficiency at a speed relevant to trained male distance runners. The decrease was not exaggerated; it corresponded to a mean improvement of approximately 3.8%, which is plausible for an 8-week intervention in trained athletes.

Figure 4 presents the change in velocity at 4 mmol·L-1 blood lactate. The HIIT group shifted from 15.46 ± 0.66 to 16.11 ± 0.74 km/h, while the control group changed from 15.42 ± 0.68 to 15.59 ± 0.79 km/h. Blood lactate also fell more after HIIT during the 14-km/h stage. Together, these findings indicate that the same submaximal speed imposed a lower metabolic burden after the intervention, and that threshold-related running speed moved rightward in the HIIT group.

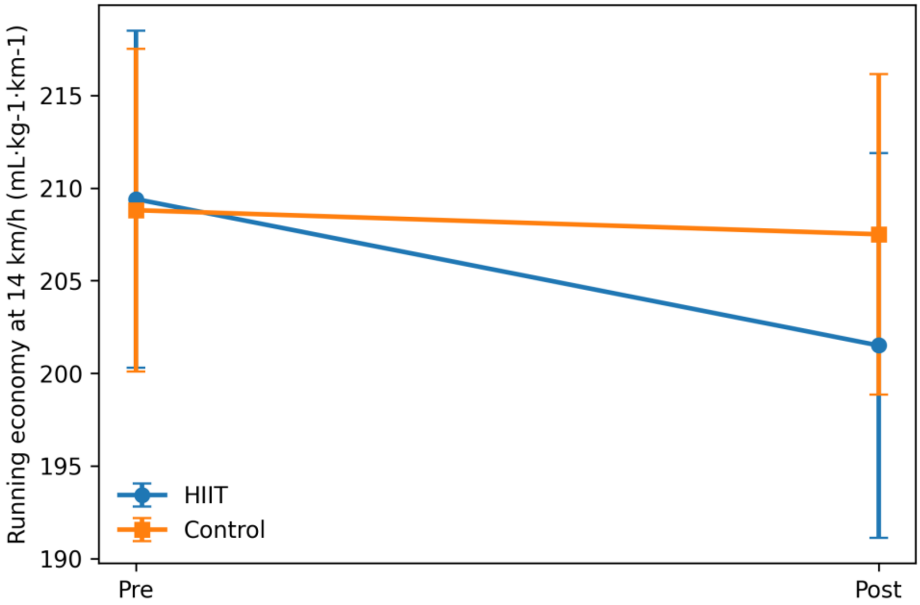


FIGURE 3. Running economy at 14 km/h before and after the intervention. Lower values indicate better running economy.

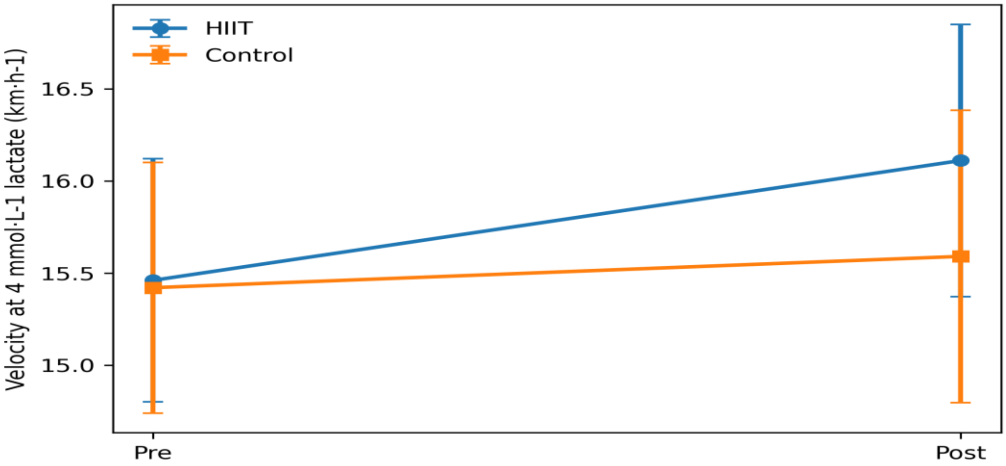


FIGURE 4. Velocity at 4 mmol·L-1 blood lactate before and after the intervention. A higher value indicates a faster threshold-related running speed.

Figure 5 shows the time-to-exhaustion at velocity at VO2max. The HIIT group improved from 361 ± 52 to 418 ± 53 s, whereas the control group improved from 358 ± 49 to 368 ± 52 s. The increase in the HIIT group represented a 15.8% improvement and was accompanied by smaller improvements in VO2max and velocity at VO2max. This pattern indicates that the severe-intensity tolerance outcome improved more than could be explained by VO2max alone.

Figure 6 displays individual percentage improvements in the HIIT group for the three primary outcomes. Most runners improved in at least two of the three outcomes, but the size of the response varied across individuals. Some athletes showed greater improvements in economy, whereas others showed the largest gains in time-to-exhaustion. This variation is expected in trained athletes and underscores the importance of monitoring individual responses rather than assuming that the same interval program has the same effect on every runner.

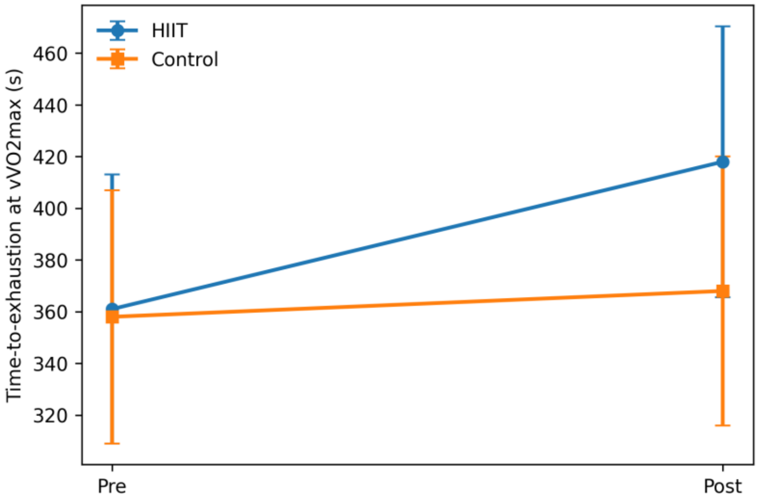


FIGURE 5. Time-to-exhaustion at velocity at VO$_2$max before and after the intervention.

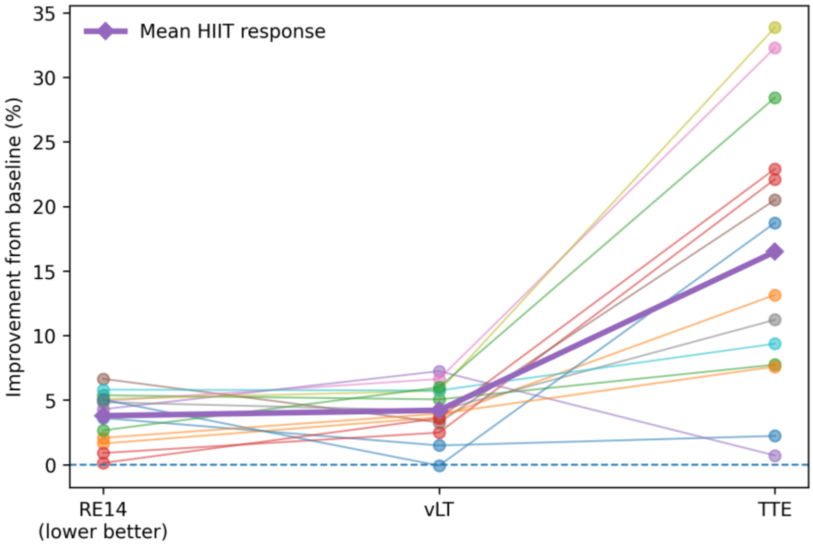


FIGURE 6. Individual HIIT responses for the three primary outcomes. Values are expressed as percentage improvement from baseline, with lower running-economy values converted to positive values to indicate improvement.

Figure 7 summarizes standardized between-group change effects. Positive values indicate a favorable change in HIIT relative to control, with signs reversed for outcomes where lower values are better. The largest effects were observed for running economy at 14 km/h, velocity at 4 mmol·L-1 lactate, velocity at VO2max, and time-to-exhaustion. Figure 8 shows that runners with larger improvements in running economy at 14 km/h tended to demonstrate larger gains in time-to-exhaustion. However, the association should be interpreted cautiously because of the modest sample size. Table 5 provides the correlation statistics for these exploratory associations.

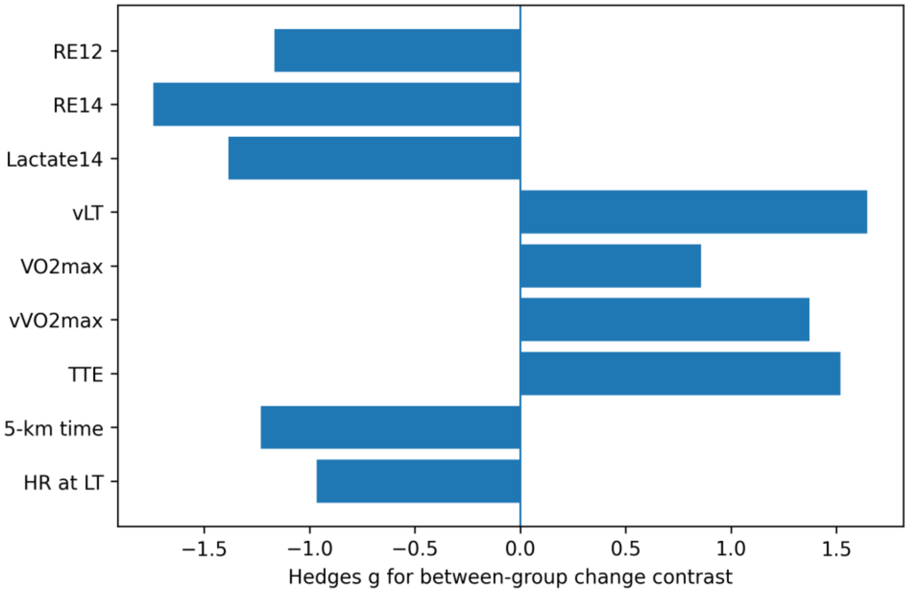


FIGURE 7. Standardized between-group change effects for primary and secondary outcomes. Bars farther from zero indicate larger standardized effects in favor of the HIIT substitution intervention.

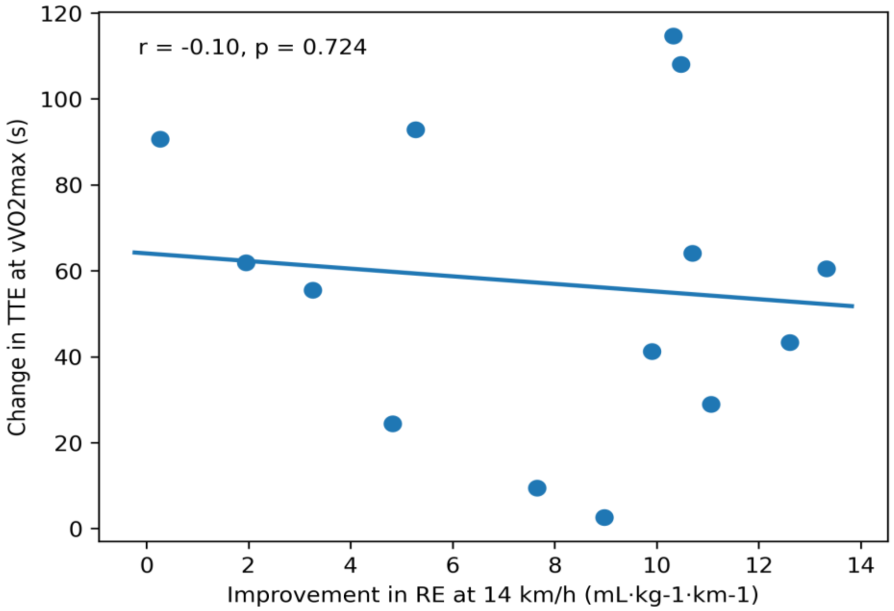


FIGURE 7. Association between improvement in running economy at 14 km/h and change in time-to-exhaustion in the HIIT group.

Table 5. Exploratory associations between changes in primary outcomes in the HIIT group.

Association within the HIIT group	r	p value
Delta RE14 vs. Delta TTE	0.10	0.724
Delta vLT vs delta TTE	0.19	0.521
Delta RE14 vs delta vLT	-0.19	0.518
Delta lactate at 14 km/h vs delta RE14	-0.00	0.993

Correlations were calculated from change scores in the HIIT group only (n = 14). These analyses were exploratory and should be interpreted with the modest sample size in mind.

V. DISCUSSION

The main finding was that an 8-week HIIT substitution program improved running economy, lactate-threshold velocity, and time-to-exhaustion in trained male distance runners without increasing total weekly training time. The intervention also produced smaller but statistically significant improvements in VO_2max, velocity at VO_2max, 5-km time-trial performance, and heart rate at lactate threshold. The pattern is meaningful because it suggests that HIIT acts through several linked pathways rather than through one isolated maximal aerobic adaptation. In trained runners, this is often the most valuable form of improvement: the athlete becomes more economical at submaximal speed, can run faster before reaching a fixed lactate concentration, and can tolerate severe-intensity running for longer.

The improvement in economy is consistent with previous work showing that running economy is trainable, albeit usually in modest amounts, in trained athletes. The 3.8% improvement at 14 km/h aligns with the idea that economy changes do not need to be large to matter in trained runners [1]-[3]. Fletcher et al. and Foster and Lucia argued that the economy reflects more than oxygen uptake alone [11], [12]. The HIIT sessions required repeated exposure to fast but controlled running, which may have improved stride timing, postural control, and force application. Because no biomechanical data were collected, the exact mechanism cannot be confirmed, but the observed reduction in oxygen cost is consistent with a combined metabolic and neuromuscular adaptation.

The lactate-threshold findings also agree with the broader training literature. Threshold-related speed improved more after HIIT than after control training, and blood lactate at 14 km/h declined in the HIIT group. Jones and Carter described how endurance training can shift threshold-related parameters through both central and peripheral adaptations [13], and Midgley et al. emphasized that improving running performance requires attention to multiple aerobic determinants [14]. The present data extend that perspective by showing that a relatively small dose of high-intensity work can shift threshold-related running speed when it replaces part of habitual low-intensity mileage. The intervention did not require a large increase in total training time, which is important for runners who already train consistently.

Time-to-exhaustion improved more than VO2max, suggesting that severe-intensity tolerance changed beyond maximal oxygen uptake. This finding is consistent with Billat et al.'s view that time-to-exhaustion at VO2max velocity is an informative yet variable marker of high-intensity running tolerance [6]. A runner who becomes more economical and moves the lactate curve rightward should be able to sustain velocity at VO2max longer, even if VO2max improves only modestly. The correlation analysis supported this interpretation, as larger improvements in economy were associated with larger time-to-exhaustion gains in the HIIT group.

The intervention design can be compared directly with previous HIIT programming research. Billat's interval-training reviews highlighted that aerobic interval training depends on the interaction between intensity, duration, repetitions, and recovery [7], [8]. Laursen and Jenkins argued that HIIT can be especially valuable for already trained endurance athletes when optimized rather than applied generically [10]. Buchheit and Laursen later framed this optimization as a programming puzzle [16], [17]. The current 3-min interval format appears to have provided enough accumulated high-intensity work to improve performance determinants while remaining manageable across 8 weeks. The absence of injury-related withdrawal supports the view that the dose was challenging but not excessive.

The present findings are also in line with runner-specific interval studies. Smith et al. showed that individualized training using velocity at VO2max and time at that speed can improve endurance variables [18]. Denadai et al. found that interval training at high percentages of VO2max velocity can improve physiological indices and running performance in trained runners [19]. Ferley et al. reported improvements after uphill and level-grade HIIT interventions in well-trained distance runners [21], [22]. The present study adds to those findings by showing a coherent improvement pattern when HIIT is used as a substitution strategy rather than being added to existing training. This is a practical distinction because many runners cannot safely add additional high-intensity volume without modifying the rest of the week.

The results also compare well with studies showing that the economy can improve through neuromuscularly demanding training. Saunders et al. reported improved economy after short-term plyometric training [25], Paavolainen et al. linked explosive-strength training to better 5-km running performance [26], and Storen et al. showed that maximal strength training can improve economy in distance runners [27]. Although the present intervention did not include strength or plyometric training, repeated fast running may have created a running-specific neuromuscular stimulus. Unlike gym-based or plyometric interventions, HIIT also stresses oxygen delivery and metabolic control during the same session. This may explain why the present results included improvements in economy, threshold-related speed, and severe-intensity tolerance simultaneously.

Esteve-Lanao et al., Seiler and Kjerland, and Seiler's broader review suggest that successful endurance athletes generally complete much of their training at low intensity while using harder sessions selectively [28]-[30]. The present findings should therefore not be interpreted as an argument for replacing the endurance base with frequent HIIT. Rather, the study supports a more restrained conclusion: two well-controlled HIIT sessions per week can improve key outcomes when easy mileage is reduced enough to maintain total training time and a balanced recovery. This is different from adding HIIT indiscriminately to a program that is already close to the athlete's recovery limit.

The moderate sample size is a limitation, but it is also typical of controlled studies in trained athlete populations. For that reason, p-values were interpreted alongside effect sizes and the direction of individual responses. Hopkins emphasized that sport-science outcomes should be interpreted with awareness of reliability and within-athlete variation [32]. The individual plots showed that most HIIT runners improved, but not in the same way. Coaches should expect this. Some athletes may respond strongly to economy, others to threshold speed, and others to high-intensity tolerance. Monitoring oxygen cost is not always available in the field, but coaches can track workout pace, heart rate, lactate when accessible, session RPE, and repeated time-trial performance.

Several limitations should be acknowledged. First, the sample included only trained male runners, so the findings should not be generalized directly to female athletes, youth runners, or elite international competitors. Second, time-to-exhaustion is informative but not equivalent to a championship race, where tactics, drafting, environmental conditions, and pacing decisions influence performance. Third, diet, sleep, and daily stress were standardized before testing but were not continuously controlled throughout the full 8 weeks. Fourth, running mechanics, muscle-tendon stiffness, and muscle oxygenation were not measured, limiting the mechanistic interpretation of the improvement in economy. Future research should combine physiological testing with biomechanical and muscle-oxygenation measures to clarify why some runners respond more strongly than others.

VI. CONCLUSION

This study showed that a carefully programmed 8-week HIIT substitution block improved several linked determinants of endurance performance in trained male distance runners. When two weekly sessions of 3-min intervals at 90-95% of velocity at VO2max replaced a modest portion of easy mileage, runners improved running economy at 14 km/h, increased velocity at 4 mmol·L-1 blood lactate, extended time-to-exhaustion at velocity at VO2max, and improved 5-km time-trial performance more than runners who maintained habitual endurance training. VO2max and velocity at VO2max also increased; the HIIT raised one maximal value, submaximal running became less costly, threshold-related speed increased, and tolerance of severe-intensity running improved.

The results support the use of HIIT as a precise redistribution strategy rather than simply adding more hard work. Total weekly training time remained similar between groups, so a larger overall exercise dose cannot explain the observed changes. This point matters for trained runners because additional intensity is useful only when it can be absorbed. The HIIT format used here was demanding enough to adapt but structured enough to preserve control: repetitions were long enough to create substantial aerobic stress, recoveries were active, and the progression from four to six repetitions allowed a gradual increase in accumulated work. The absence of injury-related withdrawal suggests that this dose was tolerable in the present sample, although individual monitoring remains essential.

The findings reinforce the need to evaluate endurance interventions with more than one outcome. VO2max alone would have underestimated the value of the intervention, because the largest practical changes appeared in running economy, lactate-threshold velocity, and time-to-exhaustion. For coaches, the results suggest that HIIT can be useful when a runner needs to raise high-speed aerobic quality without abandoning the endurance base. Athletes with poor recovery, recent injury, or already high high-intensity load may need a smaller dose or a different placement within the week. Future studies should test whether similar effects occur in female runners, elite-level athletes, and athletes with different race specializations, and examine whether improvements in economy are driven primarily by biomechanics, muscle-tendon behavior, oxidative adaptations, or improved pacing tolerance. Until such data are available, the present results support a balanced approach: use HIIT deliberately, monitor the response, and treat it as a high-value training tool only when it replaces, rather than adds to, the existing workload.

Author Contributions

The author conducted the conceptualization, methodology, data analysis, investigation, writing, review, editing, and final approval of the manuscript.

Funding

This research received no external funding.

Data Availability

The dataset will be available from the author upon reasonable request.

Conflicts of Interest

The author declares no conflict of interest.

REFERENCES

1. D. L. Conley and G. S. Krahenbuhl, "Running economy and distance running performance of highly trained athletes," Medicine and Science in Sports and Exercise, vol. 12, no. 5, pp. 357-360, 1980, doi: 10.1249/00005768-198012050-00010.
2. P. U. Saunders, D. B. Pyne, R. D. Telford, and J. A. Hawley, "Factors affecting running economy in trained distance runners," Sports Medicine, vol. 34, no. 7, pp. 465-485, 2004, doi: 10.2165/00007256-200434070-00005.
3. K. R. Barnes and A. E. Kilding, "Running economy: measurement, norms, and determining factors," Sports Medicine - Open, vol. 1, no. 1, article 8, 2015, doi: 10.1186/s40798-015-0007-y.
4. O. Faude, W. Kindermann, and T. Meyer, "Lactate threshold concepts: how valid are they?" Sports Medicine, vol. 39, no. 6, pp. 469-490, 2009, doi: 10.2165/00007256-200939060-00003.
5. R. Beneke, R. M. Leithauser, and O. Ochentel, "Blood lactate diagnostics in exercise testing and training," International Journal of Sports Physiology and Performance, vol. 6, no. 1, pp. 8-24, 2011, doi: 10.1123/ijspp. 6.1.8.
6. V. Billat, J.-C. Renoux, J. Pinoteau, B. Petit, and J.-P. Koralsztein, "Reproducibility of running time to exhaustion at VO2max in subelite runners," Medicine and Science in Sports and Exercise, vol. 26, no. 2, pp. 254-257, 1994, doi: 10.1249/00005768-199402000-00018.
7. L. V. Billat, "Interval training for performance: a scientific and empirical practice. Special recommendations for middle- and long-distance running. Part I: aerobic interval training," Sports Medicine, vol. 31, no. 1, pp. 13-31, 2001, doi: 10.2165/00007256-200131010-00002.

8. L. V. Billat, "Interval training for performance: a scientific and empirical practice. Special recommendations for middle- and long-distance running. Part II: anaerobic interval training," Sports Medicine, vol. 31, no. 2, pp. 75-90, 2001, doi: 10.2165/00007256-200131020-00001.
9. J. Helgerud et al., "Aerobic high-intensity intervals improve VO2max more than moderate training," Medicine and Science in Sports and Exercise, vol. 39, no. 4, pp. 665-671, 2007, doi: 10.1249/mss.0b013e3180304570.
10. P. B. Laursen and D. G. Jenkins, "The scientific basis for high-intensity interval training: optimizing training programs and maximizing performance in highly trained endurance athletes," Sports Medicine, vol. 32, no. 1, pp. 53-73, 2002, doi: 10.2165/00007256-200232010-00003.
11. J. R. Fletcher, S. P. Esau, and B. R. MacIntosh, "Economy of running: beyond the measurement of oxygen uptake," Journal of Applied Physiology, vol. 107, no. 6, pp. 1918-1922, 2009, doi: 10.1152/japplphysiol. 00307.2009.
12. C. Foster and A. Lucia, "Running economy: the forgotten factor in elite performance," Sports Medicine, vol. 37, no. 4-5, pp. 316-319, 2007, doi: 10.2165/00007256-200737040-00011.
13. A. M. Jones and H. Carter, "The effect of endurance training on parameters of aerobic fitness," Sports Medicine, vol. 29, no. 6, pp. 373-386, 2000, doi: 10.2165/00007256-200029060-00001.
14. A. W. Midgley, L. R. McNaughton, and A. M. Jones, "Training to enhance the physiological determinants of long-distance running performance," Sports Medicine, vol. 37, no. 10, pp. 857-880, 2007, doi: 10.2165/00007256-200737100-00003.
15. E. M. Stoa et al., "Factors influencing running velocity at lactate threshold in male and female runners at different levels of performance," Frontiers in Physiology, vol. 11, article 585267, 2020, doi: 10.3389/fphys. 2020.585267.
16. M. Buchheit and P. B. Laursen, "High-intensity interval training, solutions to the programming puzzle. Part I: cardiopulmonary emphasis," Sports Medicine, vol. 43, no. 5, pp. 313-338, 2013, doi: 10.1007/s40279-013-0029-x.
17. M. Buchheit and P. B. Laursen, "High-intensity interval training, solutions to the programming puzzle. Part II: anaerobic energy, neuromuscular load and practical applications," Sports Medicine, vol. 43, no. 10, pp. 927-954, 2013, doi: 10.1007/s40279-013-0066-5.
18. T. P. Smith, L. R. McNaughton, and K. J. Marshall, "Effects of 4-wk training using Vmax/Tmax on VO2max and performance in athletes," Medicine and Science in Sports and Exercise, vol. 31, no. 6, pp. 892-896, 1999, doi: 10.1097/00005768-199906000-00019.
19. B. S. Denadai, M. J. Ortiz, C. C. Greco, and M. T. de Mello, "Interval training at 95% and 100% of the velocity at VO2max: effects on aerobic physiological indexes and running performance," Applied Physiology, Nutrition, and Metabolism, vol. 31, no. 6, pp. 737-743, 2006, doi: 10.1139/h06-080.
20. S. Seiler, K. Joranson, B. V. Olesen, and K. J. Hetlelid, "Adaptations to aerobic interval training: interactive effects of exercise intensity and total work duration," Scandinavian Journal of Medicine and Science in Sports, vol. 23, no. 1, pp. 74-83, 2013, doi: 10.1111/j.1600-0838.2011.01351.x.
21. D. D. Ferley, R. W. Osborn, and M. D. Vukovich, "The effects of uphill vs. level-grade high-intensity interval training on VO2max, Vmax, VLT, and Tmax in well-trained distance runners," Journal of Strength and Conditioning Research, vol. 27, no. 6, pp. 1549-1559, 2013, doi: 10.1519/JSC.0b013e3182736923.
22. D. D. Ferley, R. W. Osborn, and M. D. Vukovich, "The effects of incline and level-grade high-intensity interval treadmill training on running economy and muscle power in well-trained distance runners," Journal of Strength and Conditioning Research, vol. 28, no. 5, pp. 1298-1309, 2014, doi: 10.1519/JSC.0000000000000274.
23. F. M. Iaia, Y. Hellsten, J. J. Nielsen, M. Fernström, K. Sahlin, and J. Bangsbo, "Four weeks of speed endurance training reduces energy expenditure during exercise and maintains muscle oxidative capacity despite a reduction in training volume," Journal of Applied Physiology, vol. 106, no. 1, pp. 73-80, 2009, doi: 10.1152/japplphysiol. 90676.2008.
24. Z. Milanović, G. Sporiš, and M. Weston, "Effectiveness of high-intensity interval training and continuous endurance training for VO2max improvements: a systematic review and meta-analysis of controlled trials," Sports Medicine, vol. 45, no. 10, pp. 1469-1481, 2015, doi: 10.1007/s40279-015-0365-0.
25. P. U. Saunders et al., "Short-term plyometric training improves running economy in highly trained middle and long distance runners," Journal of Strength and Conditioning Research, vol. 20, no. 4, pp. 947-954, 2006, doi: 10.1519/R-18235.1.
26. L. Paavolainen, K. Hakkinen, I. Hamalainen, A. Nummela, and H. Rusko, "Explosive-strength training improves 5-km running time by improving running economy and muscle power," Journal of Applied Physiology, vol. 86, no. 5, pp. 1527-1533, 1999, doi: 10.1152/jappl. 1999.86.5.1527.
27. O. Storen, J. Helgerud, E. M. Stoa, and J. Hoff, "Maximal strength training improves running economy in distance runners," Medicine and Science in Sports and Exercise, vol. 40, no. 6, pp. 1087-1092, 2008, doi: 10.1249/MSS.0b013e318168da2f.
28. J. Esteve-Lanao, C. Foster, S. Seiler, and A. Lucia, "Impact of training intensity distribution on performance in endurance athletes," Journal of Strength and Conditioning Research, vol. 21, no. 3, pp. 943-949, 2007, doi: 10.1519/R-19725.1.

29. K. S. Seiler and G. O. Kjerland, "Quantifying training intensity distribution in elite endurance athletes: is there evidence for an optimal distribution?" Scandinavian Journal of Medicine and Science in Sports, vol. 16, no. 1, pp. 49-56, 2006, doi: 10.1111/j.1600-0838.2004.00418.x.
30. S. Seiler, "What is best practice for training intensity and duration distribution in endurance athletes?" International Journal of Sports Physiology and Performance, vol. 5, no. 3, pp. 276-291, 2010, doi: 10.1123/ijspp. 5.3.276.
31. C. Foster et al., "A new approach to monitoring exercise training," Journal of Strength and Conditioning Research, vol. 15, no. 1, pp. 109-115, 2001, doi: 10.1519/00124278-200102000-00019.
32. W. G. Hopkins, "Measures of reliability in sports medicine and science," Sports Medicine, vol. 30, no. 1, pp. 1-15, 2000, doi: 10.2165/00007256-200030010-00001.