How does high-intensity intermittent training affect recreational endurance runners? Acute and chronic adaptations: A systematic review

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Abstract

Objective: This systematic review aimed to critically analyze the literature to determine how high-intensity intermittent training (HIIT) affects recreational endurance runners in the short- and long-term.

Methods: Electronic databases were searched for literature dating from January 2000 to October 2015. The search was conducted using the key words “high-intensity intermittent training” or “high-intensity interval exercise” or “interval running” or “sprint interval training” and “endurance runners” or “long distance runners”. A systematic approach was used to evaluate the 783 articles identified for initial review. Studies were included if they investigated HIIT in recreational endurance runners. The methodological quality of the studies was evaluated using the Physiotherapy Evidence Database (PEDro) scale (for intervention studies) and the modified Downs and Black Quality Index (for cross-sectional studies).

Results: Twenty-three studies met the inclusionary criteria for review. The results are presented in 2 parts: cross-sectional (n = 15) and intervention studies (n = 8). In the 15 cross-sectional studies selected, endurance runners performed at least 1 HIIT protocol, and the acute impact on physiological, neuromuscular, metabolic and/or biomechanical variables was assessed. Intervention studies lasted a minimum of 4 weeks, with 10 weeks being the longest intervention period, and included 2 to 4 HIIT sessions per week. Most of these studies combined HIIT sessions with continuous run (CR) sessions; 2 studies’ subjects performed HIIT exclusively.

Conclusion: HIIT-based running plans (2 to 3 HIIT sessions per week, combining HIIT and CR runs) show athletic performance improvements in endurance runners by improving maximal oxygen uptake and running economy along with muscular and metabolic adaptations. To maximize the adaptations to training, both HIIT and CR must be part of training programs for endurance runners.

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Keywords: Endurance; High-intensity training; Intermittent exercises; Interval running; Long-distance runners; Running

1. Introduction

Running has no age or gender restrictions, and it does not require expensive equipment or workout facilities. These are just some of the reasons that make running an increasingly popular sport. As the popularity of races such as the New York, London, and Madrid marathons shows, there is a growing number of recreational runners becoming involved in competition. Runners essentially pursue 2 objectives: (1) to improve their athletic performances and (2) to be healthy enough to keep training and achieving their aims.

With respect to the first objective, recent reviews have highlighted the potential of varying quantities of both high-intensity intermittent training (HIIT) and continuous high-volume, low-intensity training on performance in athletes.1–3 Although there is no doubt that both types of training can effectively improve cardiac and skeletal muscle metabolic function4,5 and that a dose of both types of training is an important constituent of an athlete’s training program, endurance runners often think “more is better” and so accumulate great volumes of running kilometers,6 spending most of their time training at low or moderate intensities.6

A growing body of literature highlights the role of mean training intensity over a season in optimizing athletic performance.1,4,5,7,8 A clear example for endurance runners was reported by Billat et al.,4 who showed that male Kenyan runners
training at higher speeds had a significantly better 10 km performance than Kenyan athletes training at lower speeds, despite the elite status of both groups. In this context, as a type of training that results in athletes running faster, previous studies have remarked on the importance of HIIT for maximizing performance in endurance athletes. Although there is no universal definition, HIIT generally refers to repeated short to long bouts of high-intensity exercise—performed at close to 100% maximal oxygen uptake (VO$_{2\text{max}}$)—interspersed with recovery periods, and it is considered one of the most effective forms of exercise for improving the physical performance of athletes.$^{1,4,5,7,8}$

Compared with lower-intensity cyclic workloads, intensive running requires activation of a larger motor unit, with increased recruitment of fast oxidative and glycolytic muscle fibers and an increase in the intensity of chemical processes in the muscle.$^{17,18}$ Additionally, increases in running speed lead to greater levels of neuromuscular engagement (mainly in the hamstring muscles).$^{19}$ Likewise, some differences have been observed between HIIT protocols (with different durations of work and relief intervals) in both physiological and neuromuscular impact.$^{20-26}$ Coaches must themselves decide how to manage HIIT inclusion in running plans for endurance athletes, so knowledge about the acute changes induced by HIIT protocols and the long-term adaptations induced by HIIT-based interventions in endurance runners plays a key role in the training prescription.

Because there is strong evidence that a greater training distance per week is a risk factor for lower extremity running injuries,$^{27}$ HIIT also seems to be an “interesting option” for avoiding injuries (regarding the second aim mentioned at the beginning of this section, “to be healthy enough to keep training and achieving their aims”). The incidence of running-related injuries on an annual basis is high, occurring in 40% to 50% of runners.$^{28}$ Even though it is widely accepted that injuries in endurance runners are multifactorial, it is also well known that running-related injuries are often attributable to training errors.$^{29}$ Because of a lack of studies evaluating injury occurrence, the effects of more strenuous runs on markers related to risk of injury are still unknown, so this review mainly focuses on the effects of HIIT on endurance performance.

To the best knowledge of the authors, 14 reviews have so far been written about HIIT, of which only 2 were systematically performed by and included information about literature search strategies. Five of these 14 studies focused on sprint interval training (SIT), with work periods at maximal intensities,$^{10-14}$ whereas the other 9 considered different HIIT regimens at submaximal intensities. As for the type of population, 3 studies focused on active healthy people,$^{12,13,15}$ whereas the other 11 related to trained athletes. Among them, only Billat$^{6}$ focused on endurance runners, with 2 works published in 2001. Therefore, a systematic review that summarizes findings and new evidence about how HIIT affects recreational endurance runners from a multidisciplinary perspective (physiological, neuromuscular, and biomechanical) in the short and long term is needed, and this is the main purpose of the current work.

### 2. Methods

#### 2.1. Search strategy

Electronic databases, including PubMed, ScienceDirect, Web of Science, and SPORTDiscuss, were searched for literature dating from January 2000 to October 2015. The keywords used were “high-intensity intermittent training” or “high-intensity interval exercise” or “interval running” or “sprint interval training” and “endurance runners” or “long distance runners”. The search was limited based on text availability (full-text available), publication date (from January 2000 to October 2015), species (humans), language (English), and age (≥18 years). Duplicates between searches were removed. Results of the search procedures are summarized in Fig. 1.

#### 2.2. Selection criteria

Studies were included in the review if they met the following criteria: (1) published in peer-reviewed journals; (2) included participants 18 years or older; (3) involved recreational endurance runners; and (4) used run-based testing sessions and, in the case of intervention studies, run-based training programs. Studies were excluded if they (1) did not meet the minimum requirements of an experimental study design (e.g., case reports), (2) did not meet the minimum requirements regarding...
training design (e.g., lack of information on volume, frequency, and/or intensity of training), (3) were not written in English, or (4) involved untrained subjects, team sport athletes, or nonendurance runners. Additionally, review articles were not included in this systematic review. Based on the inclusion and exclusion criteria, 2 independent reviewers (FGP and PALR) screened the citations of potentially relevant publications. If the citation showed any potential relevance, it was screened at the abstract level. When abstracts indicated potential inclusion, full-text articles were reviewed. A third-party consensus meeting was held with a third author (VMSH) if the 2 reviewers were not able to reach agreement on inclusion of an article.

2.3. Quality assessment

For cross-sectional studies (those focused on examining the acute effects of HIIT protocols on physiological, metabolic, neuromuscular, and biomechanics measurements), quality was assessed using the modified version of the Quality Index developed by Downs and Black.30 The original scale was reported to have good test–retest (r = 0.88) and inter-rater (r = 0.75) reliability and high internal consistency (Kuder–Richardson Formula 20 (KR-20) = 0.89). The modified version of the Downs and Black Quality Index is scored from 1 to 14, with higher scores indicating higher-quality studies.

For intervention studies (those focused on the impact of HIIT-based running programs on physiological, metabolic, neuromuscular, and biomechanics measurements), methodological quality was assessed using the Physiotherapy Evidence Database (PEDro) scale,31 an 11-item scale that rates randomized controlled trials from 0 to 10, with 6 representing the cutoff score for high-quality studies. One question was used to establish external validity and was not included in the score. Only studies with PEDro scores of 6 or higher were considered for the systematic review.31 Maher et al.31 demonstrated fair-to-good inter-rater reliability with an intraclass correlation coefficient of 0.68 when using consensus ratings generated by 2 or 3 raters. Eight studies met the inclusion criteria.32–39 Consensus was achieved on scores given to the 8 articles.

For both cross-sectional and intervention studies, 2 independent reviewers (FGP and PALR) performed quality assessments of the included studies, and disagreements were resolved through a consensus meeting or a rating by a third assessor (VMSH).

3. Results

The results for cross-sectional and longitudinal studies are presented separately. Table 1 (cross-sectional studies, n = 15) and Table 2 (intervention studies, n = 8) summarize the essential parameters of the selected studies.

3.1. Cross-sectional studies

Results from the Downs and Black scale are shown in Table 3. Scores for the Downs and Black scale ranged from 9 to 12 of a possible 14. Of particular note was that no study included a sample size representative of the entire population (Item 12) or considered confounding factors (Item 25).

As for the cross-sectional studies selected in Table 1 (n = 15), some focused on describing the response to a specific HIIT running protocol,40–42 whereas others made a comparison between the responses to HIIT and a continuous run (CR),20,43,44 or between different HIIT running protocols.21–26,45–47 In the study by García-Pinillos et al.,47 participants performed typical running workouts, varying in intensity (in terms of average running pace), duration of work, and rest intervals but with similar density and total distance (4 km). Similarly, Kaikkonen et al.21 utilized running protocols with the same volume (3 km) but different intensity (85%–105% velocity associated to VO2max (vVO2max)) and different durations of work and rest periods. On the other hand, Seiler and Hetlelid22 and Collins et al.45 focused on the manipulation of resting time but maintained work intervals, with workouts performed at a self-selected pace, whereas Millet et al.,46 Wallner et al.,23 and Billat et al.24 maintained constant work and rest intervals but modified the intensity (30–30 s during Tmin, 10–20 s during 30 min, and 15–15 s up to exhaustion, respectively). Finally, Vuorimaa et al.23 and Seiler and Sjursen26 compared HIIT protocols with

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Table 1

| Study | Subject description | Study design | Exercise protocol | Outcome measure | Result |
|-------|---------------------|--------------|-------------------|-----------------|--------|
| Latorre et al. (2014)46 | n = 16 M | Unilateral crossover | 4 × 3 × 400 m | Physiological response: | - CMJ and HS performances are equal despite high level of exhaustion |
| | 29.6 ± 7.0 years | All participants performed the running protocol | 12 runs of 400 m, grouped into 4 sets of 3 runs, with 1 min passive recovery between runs and 3 min between sets | | - CMJ performance (resting vs. 1st set): postactivation potentiation |
| | BMI 23 ± 2 kg/m² | A field-based study (on a track) | vVO2max | Neurovascular response: | - ↑ cortisol concentration after the HIIT, compared with others |
| | VO2max 56 ± 3 mL/kg/min | - Nonelite | - HIIT: 6 runs of 3.5 min at 90%vVO2max, with 2 min of recovery at 30%vVO2max | Athletic performance: | - ↑ testosterone postexercise in both running-based exercise trials (over 50% higher than pre-exercise) |
| Tanner et al. (2014)48 | n = 10 M | Repeated measures | - HR and hormone response (cortisol and testosterone) | - Running speed |
| | 39.3 ± 6.0 years | All participants completed 5 trials in random order | - CMJ: 30 min at LT | - %VO2max |
| | 76.6 ± 8.0 kg | - Laboratory conditions | Body weight–only circuit session | - 50% higher than pre-exercise |
| | VO2max 59 ± 6 mL/kg/min | - Recreational | - CR: 30 min at LT | | |
| | - 4–8 session/week | - 40–42 | | | |
| | | | | | |

(continued on next page)
| Study                  | Subject description | Study design            | Exercise protocol | Outcome measure                      | Result                                                                 |
|-----------------------|---------------------|-------------------------|-------------------|---------------------------------------|------------------------------------------------------------------------|
| García-Pinillos et al. (2016) | n = 18 (16 M, 2 F) | Repeated measures       | - HIIT: 10 × 400 m, 90 s recovery between runs | Physiological response: - BLa and HR                                 | - Despite equal training volumes (4 km), 40 × 100 m enabled runners to train at a higher pace (+3.13 km/h) |
|                       | 30.9 ± 11.0 years | All participants        | - HIIT: 40 × 100 m, 30 s recovery between runs | Neuromuscular response: - Postural control, jumping test, SSC         |                                                                        |
|                       | BMI 22 ± 2 kg/m²   | completed 2 trials in   | - A passive recovery between runs | Athletic performance: - Running pace                                  |                                                                        |
|                       | vVO₂max, 17 ± 1 km/h | random order            | - Both protocols were carried out > vVO₂max |                                                                        |                                                                        |
|                       | - Recreationally trained | - A field-based study (on a track) |                                                                        |                                                                        |                                                                        |
|                       | - 4–6 session/week |                                                                        |                                                                        |                                                                        |                                                                        |
| Hernández-Torres et al. (2009) | n = 15 M | Repeated measures       | 2 single exercise sessions of equal duration (90 min) | Physiological response: - BLa and HR                                 | - HIIT: VO₂max higher level of intensity than CR (%HRmax = +13.8%; %VO₂max = +14.83%; RER = 5.83%), and ↑ EE |
|                       | 22.8 ± 5.0 years  | All participants        | and distance (14 km) | - BLa and HR                                      |                                                                        |
|                       | BMI 20 ± 2 kg/m²   | completed 2 trials in   | - CR: ~45%VO₂max | Metabolic response: - EE and RER                |                                                                        |
|                       | VVO₂max           | random order            | - HIIT: 22 reps of   |                                                                        |                                                                        |
|                       | 77 ± 3 mL/kg/min  | - Laboratory conditions | -40%VO₂max for 3 min and |                                                                        |                                                                        |
|                       | - 5–6 session/week |                                                                        | ~75%VO₂max for 1 min |                                                                        |                                                                        |
|                       | - >1 year training |                                                                        |                                                                        |                                                                        |                                                                        |
|                       | BMI 22 ± 2 kg/m²   | - Trained athletes      |                                                                        |                                                                        |                                                                        |
|                       | VVO₂max           | - Laboratory conditions |                                                                        |                                                                        |                                                                        |
|                       | 72 ± 5 mL/kg/min  |                                                                        |                                                                        |                                                                        |                                                                        |
|                       | - 4–5 session/week |                                                                        |                                                                        |                                                                        |                                                                        |
|                       | - Trained athletes |                                                                        |                                                                        |                                                                        |                                                                        |
|                       | 30.0 ± 4.0 years  | Repeated measures       | 6 × 4 min work butts with either 1, 2, or 4 min recovery periods were performed in each session | Physiological response: - BLa and HR                                 | - Running velocity: ↑ recovery time (1–2 min) resulted in a ↑ 2% average pace; resting 4 min = work intensity |
| Steller and Hetlelid (2005) | n = 9 M | All participants        | - Self-paced: the highest possible average running speed for the work protocols | - Gas exchange                                                      |                                                                        |
|                       | 72 ± 5 kg         | completed 3 treadmill HIITs in random order | - HIIT: 2 × 6 × 250 m/rec | Athletic performance: - Running velocity |                                                                        |
|                       | 181 ± 6 cm        | HIITs in random order   | 30 s/5 min at 85%VO₂max |                                                                        |                                                                        |
|                       | VVO₂max           | - Laboratory conditions | - HIIT: 2 × 3 × 500 m/rec |                                                                        |                                                                        |
|                       | 72 ± 5 mL/kg/min  |                                                                        | 1 min/5 min at 85%VO₂max |                                                                        |                                                                        |
|                       | - 4–5 session/week |                                                                        | - HIIT: ≥ 2 × 6 × 250 m/rec |                                                                        |                                                                        |
|                       | - Trained athletes |                                                                        | 30 s/5 min at 105%VO₂max |                                                                        |                                                                        |
| Kaikkonen et al. (2012) | n = 13 M | Repeated measures       | 3 HIITs for equal distance (3 km) | Physiological response: - VO₂, CO₂, and EPOC | - High exhaustion level (RPE = 18; HRpeak = 182 bpm; HRrec = 155 bpm; and BLa = 14 mmol/L) |
|                       | 35.0 ± 5.0 years  | All participants        | - HIIT:2 × 6 × 250 m/rec | - BLa, HR and HR | - Despite that, in trained subjects equal strength and power levels and work capacity |
|                       | BMI 76.6 ± 5.6 kg | completed 3 treadmill HIITs in random order | 30 s/5 min at 85%VO₂max | CMJ and HS |                                                                        |
|                       | VVO₂max           | - Laboratory conditions | - HIIT:2 × 3 × 500 m/rec | Athletic performance: - Running pace |                                                                        |
|                       | 54 ± 3 mL/kg/min  |                                                                        | 1 min/5 min at 85%VO₂max |                                                                        |                                                                        |
|                       | - Recreational     |                                                                        | - HIIT: ≥ 2 × 6 × 250 m/rec |                                                                        |                                                                        |
|                       | - 4–5 session/week |                                                                        | 30 s/5 min at 105%VO₂max |                                                                        |                                                                        |
| García-Pinillos et al. (2015) | n = 30 M | Unilateral crossover    | 4 × 3 × 400 m       | Physiological response: - BLa, HR                  | - After HIIT sessions at 100%VVO₂max the VO₂ independent of the recovery condition ↓ RE after HIIT |
|                       | 38.2 ± 8.0 years  | All participants        | 12 runs of 400 m, grouped into 4 sets of 3 runs, with 1 min passive recovery between runs, and 3 min between sets | Neuromuscular response: - CMJ and HS | Irrespective of the duration of recovery, running kinematics equal |
|                       | BMI 22 ± 3 kg/m²   | performed the HIIT      | - (a field-based study) | Athletic performance: - Running pace |                                                                        |
|                       | VVO₂max           | (on a track)            | 4 × 3 × 400 m       | Physiological response: - VO₂, and RER |                                                                        |
|                       | 58 ± 4 mL/kg/min  |                                                                        | 4.47 m/s           | - RE (based on VO₂) |                                                                        |
|                       | - Recreational     |                                                                        | - 10 × 400 m, 1 min rec | Kinematic data: - 2D analysis |                                                                        |
|                       | - 5–8 session/week |                                                                        | - 10 × 400 m, 2 min rec | Athletic performance: - Running pace |                                                                        |
|                       | 25.4 ± 4.0 years  | Repeated measures       | 3 HIIT sessions with running economy tests at 3.33 and 4.47 m/s | Physiological response: - VO₂, and RER |                                                                        |
| Collins et al. (2009)  | n = 7 M          | All participants        | - HIIT sessions at 100%VVO₂max | - VO₂ independent of the recovery condition |                                                                        |
|                       | 25.4 ± 4.0 years  | completed 3 treadmill HIITs in random order | 4.47 m/s           | - RE after HIIT |                                                                        |
|                       | 68.8 ± 7.4 kg     | - Laboratory conditions | - 10 × 400 m, 1 min rec | Irrespective of the duration of recovery, running kinematics equal |                                                                        |
|                       | 180 ± 7 cm        |                                                                        | - 10 × 400 m, 2 min rec |                                                                        |                                                                        |
|                       | VVO₂max           |                                                                        | - 10 × 400 m, 3 min rec |                                                                        |                                                                        |
|                       | 72 ± 3 mL/kg/min  |                                                                        | - Protocols were carried out at vVO₂max |                                                                        |                                                                        |
|                       | - >1 year of training |                                                                        | - HIIT: ≥ 14 × 60 s runs with 60 s rest at vVO₂max | - VO₂ independent of the recovery condition |                                                                        |
|                       | 22 ± 3 years      | Repeated measures       | - HIIT: ≥ 14 × 60 s runs with 60 s rest at vVO₂max | - RE after HIIT |                                                                        |
| Vuorimaa et al. (2009) | n = 10 M          | All participants        | - HIIT sessions at 100%VVO₂max | - VO₂ independent of the recovery condition |                                                                        |
|                       | 66.7 ± 7.0 kg     | completed 2 trials in   | 4.47 m/s           | - RE after HIIT |                                                                        |
|                       | 178 ± 5 cm        | random order            | - 10 × 400 m, 1 min rec | Irrespective of the duration of recovery, running kinematics equal |                                                                        |
|                       | VVO₂max           | - Laboratory conditions | - 10 × 400 m, 2 min rec |                                                                        |                                                                        |
|                       | 72 ± 3 mL/kg/min  |                                                                        | - 10 × 400 m, 3 min rec |                                                                        |                                                                        |
|                       | - Trained runners  |                                                                        | - Protocols were carried out at vVO₂max | - VO₂ independent of the recovery condition |                                                                        |
|                       | - National level  |                                                                        | - HIIT: ≥ 14 × 60 s runs with 60 s rest at vVO₂max | - RE after HIIT |                                                                        |

(continued on next page)
| Study            | Subject description | Study design | Exercise protocol                                                                 | Outcome measure                                                                                       | Result                                                                                           |
|------------------|---------------------|--------------|------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------|
| Millet et al.    | n = 7 M             | Repeated measures | 2 HIIT sessions consisting of (n x 30 s = Tlim)                                    | Physiological parameters: V02peak and running pace ↓ HIIT105% than in HIIT100%                          | - VO2peak and running pace ↓ HIIT105% than in HIIT100%                                          |
|                  | 21 ± 3.0 years      | All participants completed 2 HIITs in random order | - HIIT100%: 30 s work intervals at 100%VO2max with 30 s rec at 50%VO2max         | - V02 and VO2max                                                                                       | - HIIT100% than in HIIT100%                                                                     |
|                  | 64.7 ± 6.0 kg       | - Endurance athletes - 40–60 km/week | - HIIT160%: identical, but work intervals at 105%VO2max                           | Performance variables: Time (s) ≥ 90%HRmax                                                          | - HIIT100% than in HIIT100%                                                                     |
|                  | VO2max              | - 72 ± 3 mL/kg/min | - HIIT160%: identical, but work intervals at 105%VO2max                           | Time (s) ≥ 90%HRmax                                                                                        | - HIIT100% than in HIIT100%                                                                     |
| Wallner et al.   | n = 8 M             | Repeated measures | 3 HIITs were performed at vO2max (10 s work, 20 s passive rec, during 30 min)     | Physiological parameters: - VO2 and VO2max                                                           | - Short HIITs with passive rest phases gave an overall aerobic metabolic profile similar to CR      |
|                  | 24.5 ± 3.0 years    | All participants completed 3 HIITs in random order | - VO2max at ≥ 90%VO2max                                                           | Performance variables: - VO2 and VO2max                                                             | - Mean VO2 in ascending order of intensity.                                                        |
|                  | BMI 22 ± 1 kg/m²     | - Laboratory conditions | - HIIT with a 2:1 work–rest ratio. Exercise periods at 90%–95%VO2max during      | - VR and BLa                                                                                           | - BLA equals level at the end of warm-up                                                         |
|                  | VO2max              | - 55 ± 3 mL/kg/min | 50%TVLT, whereas rec periods at 50%TVLT, during 50%TVLT                           | - VO2peak with lower BLa                                                                               |                                                                                                  |
|                  | - Trained male      | - 45 ± 7 years | - CR: up to exhaustion at 90%–95%VO2max                                            | - PeakVO2 ↑ during HIIT                                                                                 |                                                                                                  |
|                  | runners             | F: 51 ± 3 kg | - HIIT with a 2:1 work–rest ratio. Exercise periods at 90%–95%VO2max during      | - ↑ time running > 90%VO2max during HIIT                                                             |                                                                                                  |
| Demarie et al.   | n = 15 (3 F, 12 M)  | Repeated measures | - A field-based study (on a track)                                                | - HIIT resulted better than CR to stimulate aerobic metabolism with ↑ Tlim, longer time at vO2max and | - HIIT: ↑ time HRmax was performed at ↑ velocity, and equal to or ↓ BLa                           |
|                  | 45 ± 7 years        | All participants completed 3 sessions | - HIIT with a 2:1 work–rest ratio. Exercise periods at 90%–95%VO2max during      | - HIIT, ↑ time at VO2max and vO2peak with lower BLa                                                   |                                                                                                  |
|                  | F: 51 ± 3 kg        | - Subelite - VO2max | 50%TVLT, whereas rec periods at 50%TVLT, during 50%TVLT                           | - In all HIITs, runners reached HRpeak and VO2peak                                                   |                                                                                                  |
|                  | M: 72 ± 6 kg        | 56 ± 4 mL/kg/min | - CR: up to exhaustion at 90%–95%VO2max                                            | - HIIT: ↑ BLa, ↓ distance at vO2max, and ↓ total distance                                           |                                                                                                  |
| Billat et al.    | n = 7 M             | Repeated measures | Runs until exhaustion: - HIIT: ↑ 5 s runs alternating between 90% and 80%         | Physiological parameters: - Gas exchange data                                                         | - ↑ VO2max during recovery; no differences between the others                                      |
|                  | 51 ± 6 years        | All participants completed 3 HIITs in random order                                | vO2max - HIIT: ↑ 5 s runs alternating between 100% and 70% vO2max                              | HR and BLa                                                                                           | - HR and BLa equal across HIITs (92%–95%HRmax and 4.5 mmol/L)                                      |
|                  | 71 ± 4 kg           | - Laboratory conditions | - HIIT: ↑ 5 s runs alternating between 110% and 60% vO2max                        | Performance variables: - HR and BLa                                                                | - RPE was equal (averaged 16–17)                                                               |
|                  | 175 ± 5 cm          | (3 session/week) | - PeakVO2 ↑ during HIIT                                                              | - Performance measurements: - Running velocity                                                         | - Physiological response to short HIIT is different to HIITs lasting 2–6 min                     |
|                  | VO2max              | - 52 ± 6 mL/kg/min | - PeakVO2 ↑ during HIIT                                                              | - VO2max during recovery; no differences between the others                                      |                                                                                                  |
|                  | - Trained male      | - 50–70 km/week | - PeakVO2 ↑ during HIIT                                                              | - PeakVO2 ↑ during HIIT                                                                  |                                                                                                  |
| Seiler and       | n = 12 (9 M, 3 F)   | Repeated measures | The work–rest ratio was 1:1, and the total work was                                | Physiological parameters: - Gas exchange data                                                         | - HR and BLa equal across HIITs (92%–95%HRmax and 4.5 mmol/L)                                      |
| Sjursen (2004)   | 28 ± 5 years        | All participants completed 4 HIITs sessions in random order                      | 24 min for each session - 24 × 1 min                                                  | HR and BLa                                                                                            | - RPE was equal (averaged 16–17)                                                               |
|                  | 68 ± 10 kg          | - Laboratory conditions | - 12 × 2 min - 6 × 4 min                                                           | Perceived exertion: - RPE                                                                        | - Physiological response to short HIIT is different to HIITs lasting 2–6 min                     |
|                  | 176 ± 8 cm          | (3 session/week) | - 4 × 6 min - Self-selected running pace (as fast as possible)                      | Performance measurements: - Running velocity                                                         |                                                                                                  |
| O’Brien et al.   | n = 17 (14 M, 3 F)  | Repeated measures | The work–rest ratio was 1:1, and the total work was                                | Physiological parameters: - Gas exchange data                                                         | - HR and BLa equal across HIITs (92%–95%HRmax and 4.5 mmol/L)                                      |
|                  | 22 ± 4 years        | All participants completed 3 HIITs in a balanced random order                    | 21 min at 75% vO2max                                                                  | HR and BLa                                                                                            | - RPE was equal (averaged 16–17)                                                               |
|                  | 74 ± 11 kg          | - Laboratory conditions | - HIIT: 10 × 1 min at vO2max (1:1, resting at 50% vO2max)                      | Perceived exertion: - RPE                                                                        | - Physiological response to short HIIT is different to HIITs lasting 2–6 min                     |
|                  | VO2max              | 57 ± 9 mL/kg/min | - HIIT: 5 × 2 min at vO2max (1:1, resting at 50% vO2max)                      | Performance measurements: - Running velocity                                                         | - HR and BLa equal across HIITs (92%–95%HRmax and 4.5 mmol/L)                                      |
|                  | - Moderately        | - CR: 20 min at 75% vO2max                                                       | - Time above vO2max                                                                         | Performance measurements: - Running velocity                                                         | - Physiological response to short HIIT is different to HIITs lasting 2–6 min                     |
|                  | trained runners     | (3 session/week) | - HIIT: 5 × 2 min at vO2max (1:1, resting at 50% vO2max)                      | - Time above vO2max                                                                         |                                                                                                  |

Notes: ↑ to increase or to obtain a higher value; ↓ to impair or to obtain a lower value; ~ approximately.

Abbreviations: 2D = two dimensional; AOD = accumulated oxygen deficit; BLA = blood lactate accumulation; BMI = body mass index; bpm = beats per minute; CMJ = countermovement jump; CR = continuous run; EE = energy expenditure; EPOC = postexercise oxygen consumption; F = female; HDL-C = high-density lipoprotein cholesterol; HIIT = high-intensity intermittent training; HR = heart rate; HRmax = maximum heart rate; HRpeak = peak heart rate; HRrec = heart rate recovery; HRV = heart rate variability; HS = handgrip strength test; LT = lactate threshold; LDL-C = low-density lipoprotein cholesterol; M = male; RE = running economy; rec = recovery; rep = repetition; RER = respiratory exchange ratio; RPE = rate of perceived exertion; SSC = stretch-shortening cycle; Tlim = time to exhaustion sustained at VO2max; TC = total cholesterol; vVmax = maximal velocity of the graded maximal test; VLTP = velocity associated to lactate turn points; VO2 = oxygen consumption; VO2max = maximal oxygen uptake; VO2peak = peak oxygen uptake; vO2peak = velocity associated to VO2max.
### Table 2
Studies (n = 8) examining the impact of HIIT-based running programs on physiological, metabolic, neuromuscular, and biomechanics measurements in recreationally trained endurance runners (intervention studies).

| Study | Subject description | Training program (treatment and control groups) | Outcome measure | Result |
|-------|---------------------|-------------------------------------------------|----------------|--------|
| Bangsbo et al. (2009)15 | n = 17 M 34 ± 2 years 74 ± 2 kg 182 ± 2 cm VO₂max 63 ± 2 mL/kg/min - Moderately trained male endurance athletes (running 4–5 day/week) | - Intervention period: for a 6- to 9-week period<br>- Groups: speed endurance group (SET, n = 12) and control group (CG, n = 5)<br>- Training: SET: 25% ↓ in the weekly training but including SIT (2–3 time/week, 8–12 running bouts repeated 30 s at 95% of maximal speed with 3 min passive recovery), HIIT (4 × 4 min running at ~85% of HR<sub>max</sub> separated by 2 min of passive recovery), and 1–2 sessions of CR (75%–85% of HR<sub>max</sub>)<br>- CG: continued the endurance training (~55 km/week) | Physiological measurements: VO₂max and RER<br>- HR and blood samples (BLa and K<sup>+</sup>)<br>- Muscle analysis: ion transport proteins and enzymes<br>Performance measurements: Incremental test<br>Repeated sprint test<br>3 and 10 km | - The inclusion of SIT and HIIT with ↓ in training volume not only resulted in ↑ short-term work capacity but also ↑ 3 and 10 km performance in endurance runners<br>- The improvements were associated with an ~70% higher expression of Na<sup>+</sup>-K<sup>+</sup> pump and lower plasma K<sup>+</sup> concentrations during exhaustive running |
| Denadai et al. (2006)16 | n = 17 M 37 ± 4 years 63 ± 4 kg 166 ± 5 cm VO₂max 59 ± 6 mL/min/min - Trained endurance runners training a mean weekly volume of ~80 km divided into 6 training sessions | - Intervention period: for 4 weeks<br>- Groups: 95% or 100% of VO₂max groups<br>- Training: 2 HIIT sessions per week (at 95%–100% of VO₂max), 1 session at VLTP (2 × 20 min with 5 min of rest at 60% of VO₂max) and 3 CR (45–60 min at 60%–70% of VO₂max)<br>− 95%VO₂max: 4 intervals (60%T<sub>lim</sub> at 95%VO₂max; recovery = 30%T<sub>lim</sub> at 50% of VO₂max)<br>− 100%VO₂max: group: 5 intervals (identical to previous, but according to 100% of VO₂max) | Physiological measurements: VO₂max and RER<br>- HR and BLA<br>Performance measurements: Incremental test<br>Submaximal test<br>1.5 and 5 km time trials | - vVO₂max, RE, and performance (1.5 and 5 km) can be ↑ using a 4-week training program consisting of 2 HIIT sessions at 100% of VO₂max and 4 submaximal run sessions per week (95% of VO₂max)<br>- CG did not present significant improvement on the vVO₂max, RE, and 1.5 km running performance |
| Esfarjani and Laursen (2007)17 | n = 17 M 19 ± 2 years 73 ± 3 kg 172 ± 4 cm VO₂max 51 ± 2 mL/kg/min - Moderately trained male runners with 2–3 years of run training | - Intervention period: for 10 weeks<br>- Groups: 2 intervention groups (HIIT-based, EG1 and EG2) and 1 control group (CR-based, CG)<br>- Training: EG1: HIIT groups (EG1, and EG2): 2 HIIT sessions and 2 CR (60 min at 75% of VO₂max) each week<br>EG2: 7–12 × 30 s bouts at 130% of VO₂max with 4.5 min of recovery<br>− CG: 4 × 60 min CR (75% of VO₂max) per week | Physiological measurements: VO₂max and RER<br>- HR and BLA<br>Performance measurements: Incremental test<br>3000 m time trial | - HIIT-based running plan ↑ 3 km running performance time (~7.3%), concomitant with ↑ vVO₂max (+9.1%), vVO₂max (+6.4%), T<sub>lim</sub> (+35%), and V<sub>L1T</sub> (+11.7%).<br>- SIT improved 3 km performance (~3.4%) with simultaneous ↑ in vVO₂max (+6.2%), vVO₂max (+7.8%), and T<sub>lim</sub> (+32%), but not V<sub>L1T</sub> (+4.7%).<br>- ↑ performance and physiological variables tended to be greater using more prolonged HIIT at vVO₂max when compared with SIT<br>- 8 weeks of 10–20–30 training was effective in improving VO₂max and 5 km performance (~38 s) and lowering blood pressure (~5 mmHg)<br>- Muscle fiber area, fiber type, and capillarization were not changed after 10–20–30 training |
| Gliemann et al. (2015)15 | n = 160<br>HIT group: n = 132 (58 M, 74 F) 49 ± 1 years 73.7 ± 1.1 kg VO₂max 52 ± 1 mL/kg/min<br>CG: n = 28 (15 M, 13 F) 46 ± 2 years 73.7 ± 2.5 kg VO₂max 52 ± 4 mL/kg/min - Recreational 2-year training (>3 session/week) | - Intervention period: for 8 weeks<br>- Groups: CG and HIIT group (replacing 2 of 3 weekly sessions with 10–20–30 training)<br>- Training: CG: same plan (CR-based, HR between 75% and 85% of HR<sub>max</sub>)<br>− HIIT group: 1 × CR + 2 × 10–20–30 training per week. (10–20–30: 3–4 × 5 min running periods interspersed by 2 min of rest; each 5 min running period consisted of 5 consecutive 1 min intervals divided into 30, 20, and 10 s at an intensity corresponding to ~30%, ~60%, and ~90%–100% of maximal running speed | Physiological measurements: VO₂max and RER<br>- Blood pressure<br>- HR and BLA<br>- Blood variables: glucose, cholesterol, insulin, cortisol<br>- Muscle morphology<br>Performance measurements: Test to exhaustion<br>5000 m time trial | - The inclusion of SIT and HIIT with ↓ in training volume not only resulted in ↑ short-term work capacity but also ↑ 3 and 10 km performance in endurance runners<br>- The improvements were associated with an ~70% higher expression of Na<sup>+</sup>-K<sup>+</sup> pump and lower plasma K<sup>+</sup> concentrations during exhaustive running |

(continued on next page)
Table 2 (continued)

| Study                  | Subject description                                      | Training program (treatment and control groups)                                                                 | Outcome measure                                                                 | Result                                                                 |
|------------------------|---------------------------------------------------------|----------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------|------------------------------------------------------------------------|
| Gunnarsson and Bangsbo (2012)⁴¹ | n = 18 (12 M, 6 F)                                       | - **Intervention period:** for 7 weeks<br>- **Groups:** CG and HIIT (10–20–30 training)<br>- **Training:** 10–20–30 training concept (identical to the previous)<br>- CG: continued with their regular endurance training (CR-based)<br>- HIIT: all regular training sessions were replaced with 3 weekly 10–20–30 training sessions. In the first 4 weeks, 10–20–30 conducted 3 × 5 min intervals and, in the remaining 3 weeks, 4 × 5 min intervals per session | **Physiological measurements:**<br>- VO2max and RER<br>- Blood pressure, HR, BLa<br>- Blood variables: glucose, cholesterol, insulin, cortisol<br>- Muscle morphology<br>**Performance measurements:**<br>- Incremental test<br>- 1.5 and 5 km trials | - After 7 weeks of 10–20–30 training, with a ~50% ↓ in training volume, VO2max ↑ by 4% and performance in a 1.5 km and a 5 km run ↑ by 21 s and 48 s, respectively.<br>- Fasting blood and plasma values = CG, while HIIT group ↓ values at post-test in cholesterol and LDL<br>- Resting HR remained unchanged in both groups, but blood pressure was reduced in the HIIT group after intervention<br>- Muscle morphology equal in both groups; same occurred in BLa<br>|
| Smith et al. (2003)⁴¹  | n = 27 M<br>25 ± 1 years<br>72 ± 2 kg<br>179 ± 2 cm<br>61 ± 1 mL/kg/min<br>- Well-trained male endurance runners | - **Intervention period:** for 4 weeks<br>- **Groups:** CG (n = 9), HIIT1 (60%Tmax, n = 9) and HIIT2 (70%Tmax, n = 9)<br>- Training: HIIT groups completed 2 HIIT session/week at vVO2max and their respective Tmax duration; work–rest ratio of 1:2 was used during HIIT; HIIT groups performed 1 CR (30 min at 60%vVO2max) per week<br>- HIIT1: 6 intervals per HIIT session<br>- HIIT2: 5 intervals per HIIT session<br>- CG: Maintained current training level (low intensity, long duration training) | **Physiological measurements:**<br>- VO2max, RER, VT, and RE<br>- HR and BLa<br>**Subjective ratings:**<br>- sleep, fatigue, stress, and muscle soreness<br>**Performance measurements:**<br>- Treadmill test<br>- 3 and 5 km | - HIIT1 showed a 17 s improvement in 3 km, compared to a 7 s improvement of HIIT2; this change in HIIT1 was related to changes in VO2max and RE, and these runners improved in VT (6.8%) and Tmax (50 s) compared to 1.7% and 16 s improvements in HIIT2<br>- CR and HIIT induced similar beneficial effects in master runners, ↓ resting levels of oxidative stress biomarkers<br>- Resting lipid peroxidation levels were ↓ after training both in CR and HIIT<br>- No changes in PC resting values in both CR and HIIT<br>- The data showed ↓ 25% in urinary 8-OH-dG excretion in both CR and HIIT groups<br>- The defences against oxidative damage were lowered only in CR, not in HIIT<br>|
| Vezzoli et al. (2014)⁴¹ | n = 20 M<br>50 ± 6 years<br>69 ± 10 kg<br>174 ± 7 cm<br>- HIIT group: 45 ± 8 years<br>- National level, 45 km/week | - **Intervention period:** For 8 weeks<br>- **Groups:** 2 groups, 3 times nonconsecutively per week: CR-based (n = 10) or HIIT-based (n = 10)<br>- Training: 3 different types of training sessions were scheduled, with the total distance covered in each session being controlled:<br>- CR: (1) 64.5 min at 70%GET, (2) 58.5 min at 80%GET, and (3) 54 min at 90%GET<br>- HIIT: (1) 18 × (1 min at 120%GET and 2 min at 65%GET), (2) 18 × (1 min at 130% GET and 2 min at 65%GET), and (3) 18 × (1 min at 140% GET and 2 min at 65%GET) | **Physiological measurements:**<br>- VO2max, RER, and VT<br>- HR and BLa<br>- Blood pressure<br>**Indexes of oxidative stress in blood and urine samples:**<br>- CR and HIIT induced similar beneficial effects in master runners, ↓ resting levels of oxidative stress biomarkers<br>- Resting lipid peroxidation levels were ↓ after training both in CR and HIIT<br>- No changes in CR resting values in both CR and HIIT<br>- The data showed ↓ 25% in urinary 8-OH-dG excretion in both CR and HIIT groups<br>- The defences against oxidative damage were lowered only in CR, not in HIIT<br>|
| Zaton and Michalik (2015)⁴¹ | n = 17 (6 F, 11 M)<br>CG: 34 ± 15 years<br>70 ± 10 kg<br>174 ± 7 cm<br>EG: 34 ± 9 years<br>76 ± 7 kg<br>176 ± 12 cm<br>- Amateur long-distance runners<br>- >1 year of experience | - **Intervention period:** for 8 weeks<br>- **Groups:** 2 groups completing 8 weeks of CR-based (CG, n = 9) or HIIT-based (EG, n = 8)<br>- Training: EG performed 3 × 4 CR session/week; EG performed 2 HIIT and 1 CR session/week<br>- CG: continued to train as normal<br>- EG: HIIT, 4 × 20–30 s repetitions of maximal intensity running (covering a distance of 90–200 m); rest between each repetition was based on a 1.2 work–rest ratio and ranged from 40 s to 60 s; number of sets performed ranged from 2 to 4 | **Physiological measurements:**<br>- VO2max<br>- HR<br>- Blood variables during graded exercise test: BLa, pH, partial pressure of O2 and CO2 (pO2 and pCO2)<br>**Performance measurements:**<br>- Cooper test<br>**Physiological measurements:**<br>- VO2max<br>- HR<br>- Blood variables during graded exercise test: BLa, pH, partial pressure of O2 and CO2 (pO2 and pCO2)<br>**Performance measurements:**<br>- Cooper test<br>- CR and HIIT induced similar beneficial effects in master runners, ↓ resting levels of oxidative stress biomarkers<br>- Resting lipid peroxidation levels were ↓ after training both in CR and HIIT<br>- No changes in PC resting values in both CR and HIIT<br>- The data showed ↓ 25% in urinary 8-OH-dG excretion in both CR and HIIT groups<br>- The defences against oxidative damage were lowered only in CR, not in HIIT<br>|

Notes: ↑ to increase or to obtain a higher value; ↓ to impair or to obtain a lower value; = approximately.

Abbreviations: 8-OH-dG = 8-hydroxy-2-deoxy-guanosine; BLa = blood lactate accumulation; CG= control group; CR = continuous run; EG = experimental group; F = female; GET = gas exchange threshold; HIIT = high-intensity intermittent training; HR = heart rate; HRmax = maximum heart rate; M = male; PC = phosphocreatine; RE = running economy; RER = respiratory exchange ratio; SET = speed endurance training; SIT = sprint interval training; Tmax = time to exhaustion sustained at VO2max; Tmax ↑ time for which vVO2max can be maintained; VLTP = velocity associated to lactate turn points; VO2max ↑ maximal oxygen uptake; vVO2max = velocity associated to VO2max, VT = ventilatory threshold; Vt= = velocity associated to lactate threshold.
identical volume and work–rest ratios but differing work and rest intervals (at a $\bar{v}V_{O_2_{max}}$ and self-selected pace, respectively). Most studies used heart rate (HR) and blood lactate accumulation (BLA) to control the exhaustion level reached and to monitor the physiological and metabolic response to HIITs, whereas some of them also included hormone response, energy expenditure, lipids response, gas exchange analysis, and running economy (RE). Biomechanical variables were controlled in some of the aforementioned works whereas the impact of HIIT protocols at a neuromuscular level was assessed in 4 studies.

### 3.2. Intervention studies

PEDro scores for the 8 selected articles ranged from 6 to 7 out of a maximum of 11 (Table 4). One article was excluded because of the score obtained. Concealment of allocation is not entirely relevant in studies of this nature; given the nature of endurance training and the sample selection methods used, it is difficult for researchers to keep themselves and participants unaware of the treatment and groups involved. Blinding of subjects and therapists (i.e., trainers) was also not applicable in this case.

From the 8 articles included in Table 2, 7 used a high-volume, low-moderate intensity continuous training program for the control group. Likewise, 3 studies included 2 HIIT-based intervention groups not including a control group. All these studies lasted a minimum of 4 weeks, with 10 weeks being the longest intervention period, and included up to 2, 3, 33, 34, or 4 HIIT sessions per week. Most of these studies combined HIIT sessions with one of them.

![Image](https://via.placeholder.com/150)

**Table 3**

Modified Downs and Black scale. 

| Study Item | Item 1 | Item 2 | Item 3 | Item 4 | Item 5 | Item 6 | Item 7 | Item 8 | Item 9 | Item 10 | Item 11 | Total score (out of 14) |
|------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|------------------|
| Latorre-Román et al. (2014) | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 11 |
| Tanner et al. (2014) | 1 | 1 | 1 | 1 | 1 | 0 | 0 | U | 1 | 1 | 1 | 1 | 10 |
| García-Pinillos et al. (2016) | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 12 |
| Hernández-Torres et al. (2009) | 1 | 1 | 1 | 1 | 1 | 0 | U | 1 | 1 | 1 | 1 | 0 | 11 |
| Seiler and Hetlelid (2005) | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 12 |
| Kaikkonen et al. (2012) | 1 | 1 | 1 | 1 | 1 | 0 | 0 | U | 1 | 1 | 1 | 1 | 10 |
| García-Pinillos et al. (2015) | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 11 |
| Collins et al. (2000) | 1 | 1 | 1 | 1 | 1 | 0 | U | 1 | 1 | 1 | 1 | 1 | 10 |
| Vuorimaa et al. (2000) | 1 | 1 | 1 | 1 | 1 | 0 | U | 1 | 1 | 1 | 1 | 1 | 10 |
| Millet et al. (2003) | 1 | 1 | 1 | 1 | 1 | 0 | U | 1 | 1 | 1 | 1 | 1 | 10 |
| Wallner et al. (2014) | 1 | 1 | 1 | 1 | 1 | 0 | U | 1 | 1 | 1 | 1 | 1 | 11 |
| Demarie et al. (2004) | 1 | 1 | 1 | 1 | 1 | 0 | U | 1 | 1 | 1 | 1 | 0 | 0 | 11 |
| Bilart et al. (2001) | 1 | 1 | 1 | 1 | 1 | 0 | 0 | U | 1 | 1 | 1 | 1 | 1 | 0 |
| Seiler and Sjursen (2004) | 1 | 1 | 1 | 1 | 1 | 0 | 0 | U | 1 | 1 | 1 | 1 | 1 | 11 |
| O’Brien et al. (2008) | 1 | 1 | 1 | 1 | 1 | 0 | U | 1 | 1 | 1 | 1 | 1 | 10 |

**Table 4**

Physiotherapy evidence database scale (PEDro). 

| Study Item | Item 1 | Item 2 | Item 3 | Item 4 | Item 5 | Item 6 | Item 7 | Item 8 | Item 9 | Item 10 | Item 11 | Total score (out of 11) |
|------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|------------------|
| Bangsbo et al. (2009) | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 7 |
| Denadai et al. (2006) | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 7 |
| Esfarjani and Laursen (2007) | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 6 |
| Gliemann et al. (2015) | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 6 |
| Gunnarsson and Bangsbo (2012) | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 6 |
| Smith et al. (2003) | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 7 |
| Vezzoli et al. (2014) | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 6 |
| Zaton and Michalik (2015) | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 6 |
| Laffitte et al. (2003)* * | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 4 |

**Notes:** 0 = item was not satisfied; 1 = item was satisfied. Item 1: eligibility criteria were specified; Item 2: subjects were randomly allocated to groups; Item 3: allocation was concealed; Item 4: the groups were similar at baseline regarding the most important prognostic indicators; Item 5: there was blinding of all subjects; Item 6: there was blinding of all therapists who administered the therapy; Item 7: there was blinding of all assessors who measured at least one key outcome; Item 8: measurements of at least one key outcome were obtained from more than 85% of the subjects initially allocated to groups; Item 9: all subjects for whom outcome measurements were available received the treatment or control condition as allocated, or where this was not the case, data for at least one key outcome were analyzed by “intent to treat”; Item 10: the results of between groups statistical comparisons are reported for at least one key outcome; Item 11: the study provides both point measurements and measurements of variability for at least one key outcome.

* * This article was excluded because of the score obtained.
with CR sessions for intervention groups, with only 2 studies exclusively performing HIIT\textsuperscript{32,34} (In both studies this included 3 sessions per week). To check the effectiveness of the training programs, all these studies included gas exchange analysis during an incremental running test. Likewise, HR and BLA were used to control possible changes in the acute response to running protocols. Moreover, among the outcome measures, 1 study included some indexes of oxidative stress,\textsuperscript{22} whereas others included muscle proteins and enzymes\textsuperscript{23} or parameters related to muscle morphology.\textsuperscript{35} Blood analysis, in addition to BLA, was performed in 4 of these studies,\textsuperscript{33,35,39} whereas all studies assessed the athletic performance of participants.

4. Discussion

The purpose of this systematic review was to critically analyze the literature to determine how HIIT affects recreational endurance runners from a multidisciplinary perspective (physiological, neuromuscular, and biomechanical) in the short and long term. The main findings from the cross-sectional studies included in this review are (1) at a neuromuscular level, trained endurance runners are able to maintain an adequate muscular performance after a HIIT workout, whereas high-intensity CR impairs muscular performance; (2) at a physiological level, the main difference between CR and HIIT is the energetic metabolic pathway that is activated (there is a greater activation of anaerobic lactic metabolism during HIIT); and (3) at a biomechanical level, HIIT sessions including runs for 1–2 min and performed at intensity close to VO\textsubscript{2max} do not consistently perturb the running kinematics of trained male runners. On the other hand, the major outcomes from intervention studies included in this review are as follows: (1) HIIT-based training programs are effective in improving athletic performance in recreational endurance runners; (2) exercise bouts at an intensity close to or above the intensity corresponding to VO\textsubscript{2max} appear to be more effective in improving performance and VO\textsubscript{2max} compared with moderate-intensity exercise training; (3) HIIT-based running plans appear to be effective in improving RE in trained endurance runners; and (4) HIIT causes an increased oxidative capacity of a greater number of muscle fibers and a reduced plasma K\textsuperscript{+} concentration, which contributes to the maintenance of muscle function during intense exercise and delays the appearance of fatigue. However, caution should be exercised when interpreting these findings, owing to the heterogeneity that exists among study protocols. In the next section, acute responses to HIIT (including cross-sectional studies) and long-term adaptations to HIIT interventions (including HIIT-based training programs) are discussed separately.

4.1. Acute responses to HIIT-based running protocols

Many variables, at least 9, can be manipulated to prescribe different HIIT sessions, and, among them, the intensity and duration of work and relief intervals are the key influencing factors.\textsuperscript{3,5} Then the number of intervals and the number of series and between-series recovery durations and intensities determine the total work performed. From the analysis of cross-sectional studies included in this review, the authors state that the manipulation of each variable in isolation likely has a direct impact on metabolic, cardiopulmonary, and/or neuromuscular responses. When more than 1 variable is manipulated simultaneously, responses are more difficult to predict because the factors are inter-related, making it unclear which combination of work-interval duration and intensity, if any, is most effective in allowing an individual to spend prolonged time at vVO\textsubscript{2max} while “controlling” for the level of anaerobic engagement and/or neuromuscular load.\textsuperscript{8}

4.1.1. Acute neuromuscular changes after HIIT-based running exercises

The available evidence about neuromuscular engagement after run-based HIIT is limited. In the current review, 4 of the revised manuscripts\textsuperscript{23,41,42,47} examined the neuromuscular response to a HIIT workout in recreational endurance runners, and all of them did this through indirect measures related to muscular performance (i.e., jumping, balancing, and grip-strength testing). Whereas Latorre-Román et al.\textsuperscript{31} and García-Pinillos et al.\textsuperscript{42} examined the impact induced by a single HIIT protocol, García-Pinillos et al.\textsuperscript{47} and Vuorimaa et al.\textsuperscript{33} compared the changes induced by different HIIT workouts, but none of these studies made a comparison with a CR protocol. Despite differences in the running protocols, all were performed at a velocity close to vVO\textsubscript{2max}, accumulated longer work periods than 10 min at the aforementioned velocity, and, consequently, led to high levels of exhaustion in terms of BLA, rate of perceived exertion, and mean and peak HR.

In general, all these studies agree on the lack of impairment in muscular performance parameters for trained endurance runners performing a HIIT workout. Some of these studies\textsuperscript{41,42,47} even discussed the presence of the postactivation potentiation phenomenon, whereby there is a significant improvement in vertical jump performance after running. It is known that endurance training causes, on the one hand, a greater amount of phosphorylation of regulatory myosin light chains in slow fibers and, on the other hand, a greater resistance to fatigue, which allows for the prevalence of potentiation and may explain the postactivation potentiation presence in endurance athletes.\textsuperscript{49} Therefore, the ability to sustain adequate muscular performance and to tolerate fatigue during HIIT seems to be typical for endurance runners.

Nevertheless, none of these studies included a comparison with CR, so the effects of CR at a neuromuscular level remain unknown. Contradictory results can be found in recent literature; although some previous works have reported 8%–16% reductions in jumping test performance (drop jump and repeated jump tests) after a marathon\textsuperscript{50} and a negative influence of intensive aerobic running (6 km at velocity related to lactate threshold) on some muscle contractile characteristics (i.e., an impaired excitation–contraction coupling), a previous work by Vuorimaa et al.\textsuperscript{51} investigated acute changes in muscle activation and muscular power performance after 40 min of CR at an intensity of 80% VO\textsubscript{2max} in elite long-distance runners and showed an enhanced jumping performance postexercise.
4.1.2. Acute effect of HIIT-based running protocols on physiological parameters

Compared with CR, there is no doubt that differences in the impact of HIIT-based runs exist at a physiological level. A different hormone response, in terms of salivary cortisol and testosterone concentrations postexercise, was found after CR (30 min at lactate threshold intensity) and HIIT (6 × 3.5 min at 90% VO2max), with increased concentrations after HIIT compared with CR. O’Brien et al. found that despite total work durations of CR and HIIT protocols being similar (~20 min), HIITs with intervals decreasing from 100% to 50% of VO2max resulted in greater mean average VO2 than CR, with CR runners spending 1–7 min above 90% VO2max and no participant exceeding 90% VO2max. Similar results were found during runs up to exhaustion (both CR and HIIT, with work periods performed ~90%–95% of VO2max), with higher VO2max values reached during HIIT and longer times above 90% VO2max, so that HIIT was more effective than CR in stimulating aerobic metabolism, with a longer time to exhaustion, a longer time at vVO2max, and higher VO2max with lower BLA. Besides supporting these findings, Hernández-Torres et al. added that energy expenditure was higher during HIIT (based on higher VO2 values) and reported different effects on the lipids response; both HIIT and CR increased total cholesterol, where high-density lipoprotein cholesterol increased with HIIT and low-density lipoprotein cholesterol increased with CR. Taken together, the intermittent profile of HIIT workouts allows a high stimulation of aerobic metabolism (even greater than in CR) as well as a greater activation of anaerobic lactic metabolism. Thus, the main difference between CR and HIIT is the energetic metabolic pathway that is activated.

Different physiological responses to CR and HIIT might be expected, but what about between different HIIT protocols? Whereas some studies found differences in the physiological response to the compared protocols, others did not. Differences in protocols may make comparisons difficult. It seems clear that during short HIIT-based protocols with fixed durations of work and relief intervals (30–30 s, 15–15 s, 10–20 s), an increased intensity in terms of running pace elicits greater VO2max, BLA, peak HR, and rate of perceived exertion and a longer time above 90% of VO2max. But what happens during longer intervals? Some studies have compared the response to different HIIT protocols. By using short HIITs (100 m runs at ~130% of VO2max), a study by García-Pinillos et al. reported a physiological impact similar to the interval of the longer HIIT (based on 400 m runs at ~105% of VO2max). However, when doubling the duration of work and relief intervals (from 1–2 min) but maintaining running intensity (at vVO2max) and the work–rest ratio (1:1), the physiological demands changed significantly with increased aerobic energy release, BLA, and VO2max. In a similar study performed at a self-selected pace, Seiler and a Sjursen concluded that a higher number of shorter runs increases VO2max during recovery and decreases it during exercise, but protocols with intervals lasting 2–6 min showed a similar VO2 kinetic. Additionally, duration and intensity of relief intervals during HIIT workouts are influencing factors. In Seiler and Hetlelid’s study, longer work bouts (lasting 4 min) were undertaken, and changes in recovery periods (1, 2, or 4 min) induced a 2% increase in average work intensity with no differences in VO2. Likewise, RE impairment with changes in substrate utilization—an increased dependency on fat oxidation—has been reported after HIIT (based on 400 m runs) and independent of recovery time (1, 2, or 30 min). Taken together, HIIT protocols involving short work periods (<1 min) and work–rest ratios approximately 1:1–1:2 and that are performed close to maximum intensities (with indications such as “complete the protocol as fast as you can”) enable athletes, compared with longer HIIT or CR protocols, to train at an increased running pace (widely above vVO2max) and to elicit similar, or even greater, mean average VO2.

4.1.3. Acute fatigue-induced changes in biomechanics of running during HIIT

The effect of exertion on running kinematics has been extensively studied. However, most of these studies were performed under laboratory conditions and with athletes performing prolonged treadmill runs or running-induced fatigue protocol on treadmills. The generalization of results from studies that analyze running on a treadmill may become controversial if treadmill and overground running biomechanics are eventually not proven to be equivalent.

The evidence about changes induced by HIIT running protocols is quite limited. From all the studies included in this review, only 2 studies assessed the HIIT-induced changes to the biomechanics of running. Both agreed that HIIT sessions including runs for 1–2 min performed at intensity close to VO2max did not consistently perturb the running kinematics of trained male runners.

In turn, after CR protocols, some studies found fatigue-induced changes during running at kinematic level, for example, increased trunk inclination peak angle, decreased knee flexion angle at foot strike, increased step length with a corresponding decrease in cadence, and changes in foot strike pattern. Thus, based on the biomechanical response to CR and HIIT protocols, and being especially cautious because of the wide variety of running protocols used, the authors suggest that CR causes greater impairments to running kinematics than HIIT protocols, including runs for 1–2 min and performed at intensity close to VO2max.

Cross-sectional studies have limitations because the outcomes from correlative analyses do not allow the identification of a cause-and-effect relationship. Accordingly, intervention studies have to be conducted to detect cause-and-effect relationships. The subsequent section will discuss intervention studies that examined the effects of HIIT-based running programs on parameters related to endurance performance (neuromuscular, physiological, and biomechanical parameters).

4.2. Long-term adaptations to HIIT-based running programmes

In addition to the elevated number of variables that can influence the acute effect of every single HIIT session (see
earlier), determining the effectiveness of an intervention requires parameters such as duration (weeks or months), frequency (sessions per week), methodology (type of workouts), and periodization (progress of the training load) to be taken into consideration. Additionally, as we mentioned earlier, when coaches prescribe training programs, they essentially pursue 2 objectives: (1) to improve athletic performance and (2) to avoid injuries, so these elements will be covered in this section.

4.2.1. Changes in athletic performance after HIIT interventions

Despite differences in training programs conducted by these studies, all agree that athletic performance improved after HIIT intervention. Esfarjani and Laursen underwent the longest intervention included in this review (10 weeks) by combining CR with HIIT (at 100%VO2max, G1) or SIT (30 s runs at 130%VO2max, G2) in 4 sessions per week; performance in a 3 km time trial increased by 7.3% and 3.4% (G1 and G2, respectively). After 9 weeks of combining low-moderate intensity CR with HIIT and SIT sessions in a total of 6 sessions per week, Bangsbo et al. found that performance in 3 km and 10 km time trials increased (3.3% and 3.1%, respectively). Even during shorter interventions, the combination of habitual CR sessions with 2 HIIT sessions per week over 4 weeks has shown improvements in 1.5 km (2.0%), 3 km (1.1%–2.7%), and 5 km time trials (1.5%–2.3%). All these studies implemented traditional endurance training sessions with HIIT-based workouts, but other authors went further and prescribed running plans exclusively using HIITs. Gunnarsson and Bangsbo replaced the regular endurance-training program (high-volume and low-intensity) with a HIIT-based intervention (10–20–30 training concept) 3 times per week and reported 6% and 4% improvements in 1.5 km and 5 km time trials, respectively, after 7 weeks of intervention. Based on these results, the presence of at least 2 sessions of HIIT workouts in a running plan allows trained endurance runners to improve their athletic performance. It is also important to examine the duration of work intervals during HIIT. Some of these studies included SIT (all-out efforts lasting 20–30 s with long resting periods of 3–5 min), others aerobic HIIT with long work intervals (2–4 min at intensity of ≤100%VO2max), and others HIIT with short work intervals (lasting 20–60 s) at intensities >VO2max. Based on these findings, the authors suggest that HIIT and SIT must be a part of running plans for endurance athletes, but training periodization should take the progressive overload principle into consideration. For example, during a traditional periodization (increasing intensities and decreasing volumes), HIIT should move from long runs to shorter and faster runs, whereas SIT should be progressively included from short sprints to 25–30 s all-out efforts.

Despite the suggested association between increased running speed and running injury, none of these studies has directly measured or monitored injury risk factors during HIIT intervention. Only Smith et al. monitored subjective ratings of sleep, fatigue, stress, and muscle soreness, with no changes reported during the 4-week intervention. Therefore, it seems that consensus exists about the benefits of HIIT interventions for endurance performance, even though more longitudinal studies covering the effects of HIIT-based training programs on injury risk factors for endurance runners are needed. Moreover, why does endurance performance improve when running intensities during workouts are increased? To answer this question, long-term neuromuscular and physiological adaptations to HIIT interventions are examined next.

4.2.2. Changes in gas exchange measurements after HIIT-based running plans

Related to VO2max is the concept of RE, the energetic cost of running at a given speed. Most of these studies considered RE to be an influencing factor in endurance performance and hypothesized that including repeated bouts of faster runs (HIIT) in their running plans would lead to improvements in RE for endurance-trained runners. However, the results reported by these studies are equivocal. Whereas Gliemann et al. found no change in RE after 8 weeks of combining HIIT (10–20–30 training concept, 2 sessions per week) and CR (1 session per week), other studies reported RE improvements after 4, 6, and 9 weeks of training programs that included HIIT sessions. When one looks at the training programs performed in those studies, the equivocal results obtained may depend on 2 factors: the weekly running distance and the intensity of the HIIT. As suggested by Denadai et al., improvements in RE with HIIT may result from improved muscle oxidative capacity and associated changes in motor unit recruitment patterns. Ensuring a minimum weekly mileage is important in improving muscle oxidative capacity, and Gliemann et al. reduced it to approximately 15 km/week, although the studies reporting RE improvement reached greater weekly mileage. As for the intensity of the HIIT, the importance of neuromuscular characteristics (motor unit recruitment and contractile properties) in determining RE and performance has recently been pointed out by Nummela et al., whereas Gliemann et al. based their running plan on a 10–20–30 training concept performed on average at 85%HRmax and under 100%VO2max. The HIIT workouts included in the studies reported that RE improvements were seen at vVO2max or above. The findings of Denadai et al. support this rationale, with RE improving after the training program that included HIIT at 100%VO2max but not after HIIT at 95%VO2max. These data suggest that to improve RE in trained endurance runners, coaches should pay special attention to weekly mileage (combining HIIT and CR may be a good way to ensure a minimum mileage) and intensity of HIITs (close to or above 100%VO2max).

4.2.3. Muscular adaptations to HIIT-based running plans

Improved global oxygen consumption and delivery also correspond with changes in muscle fiber, in which Type I fibers have greater oxidative capacity than Types IIa and IIx fibers. Interval training, by affecting glycolytic capacity, may also lead to increased mitochondrial activity in Type II fibers and thus show characteristics similar to those of Type I fibers. Training at maximal and near-maximal exercise intensities also seems to be effective in creating muscular adaptations such as increases
in the activity of oxidative enzymes and expression of Na+-K+ pump subunits and lactate and H+ transporters. Moreover, HIIT causes repeated VO2 fluctuations related to changes in exercise intensity as opposed to CR, where VO2 is nearly constant during the exercise. Because of this, a higher exercise-induced oxidative stress could be expected; however, HIIT- and CR-based training programs induced similar beneficial effects in endurance runners, reducing the resting levels of oxidative stress biomarkers in plasma and urine. Therefore, because all these studies reported athletic performance improvements after a HIIT intervention longer than 7 weeks but did not all find VO2max or RE improvements, muscular adaptations to a HIIT period may play a critical role in the performance improvement of endurance runners.

On the other hand, no changes in muscle morphology occurred after 7–8 weeks of run-based training in either CR- or HIIT-based training programs. Likewise, capillary-to-fiber ratio and capillary density were unaltered after 7–8 weeks of HIIT-based running protocols (10–20–30 training concept). These data suggest that HIIT running protocols are less effective in improving capillarization than prolonged running and that 10–20–30 training evokes weaker angiogenic stimuli than moderate-intensity exercise training. Because muscle capillarization is important for the delivery of oxygen and nutrients to the exercising muscle (a higher capillary density can increase muscle-to-blood exchange surface, decrease oxygen diffusion distance, and increase red blood cell mean transit time), these findings lead the authors to support the idea that both HIIT and CR must be part of training programs for endurance runners to maximize the physiological adaptations to training.

4.2.4. Changes induced in blood variables—at rest and after exhausting runs

Most of the intervention studies included in this review collected BLa at the end of an exhaustive running protocol, with some of these studies reporting no adaptations after HIIT intervention, so it seems that improved short-term performance can occur without changes in some of the key H+ transport proteins. Bangsbo et al. found changes in BLa clearance (but not in peak BLa) in athletes who had completed the HIIT intervention, whereas the CR group remained unchanged. Because maximal muscle oxidative capacity is related to BLa removal ability, the authors suggest that the differences in BLa clearance might be due to an oxidative capacity improvement during the HIIT period. From this thinking, either the lack of changes in BLa together with the performance improvement (similar BLa despite a greater athletic performance) reported by some studies or the reduction of BLa after a running protocol performed at the same relative intensity is an indication of improved buffer capacity and H⁺ clearance in working muscle. Hence, training at high intensity can delay the accumulation of lactate in the blood, which may be due to an increased oxidative capacity of a greater number of muscle fibers and/or a reduced plasma K⁺ concentration (Plasma K⁺ contributes to the maintenance of muscle function during intense exercise). The training protocols used by these studies are different; although results must be interpreted with caution, increased intensity in a running plan seems to be effective in improving oxidative capacity when compared with a CR-based plan.

Regarding resting blood variables, 2 studies examined changes in blood hemoglobin and plasma iron, glucose, myoglobin, creatine kinase, cortisol, insulin, and triglycerides induced by intervention training programs. Although intense aerobic training is generally associated with improved blood lipid profile and insulin sensitivity, the results reported by these studies are equivocal, probably because the athletes were already trained at the beginning of the intervention.

5. Conclusion

Because HIIT running sessions lead, in the short term, to increased cortisol and testosterone concentrations, greater mean VO2, longer times above 90%VO2max, higher energy expenditure, and different effects on lipids response—and there being no reported “extra” neuromuscular strain or consistent perturbations in running kinematics (when compared with moderate-intensity CR)—they are an efficient option for endurance runners in response to demands of higher average intensities and lower weekly running distances (for injury prevention and performance improvements, respectively). Because of this, some studies have checked the effectiveness of HIIT-based running plans (minimum of 4-week program, at least 2 HIIT sessions per week, and mostly combining HIIT and CR work-outs) and have shown athletic performance improvements in trained endurance runners by improving VO2max and RE along with muscular and metabolic adaptations (increased oxidative capacity of a greater number of muscle fibers and reduced plasma K⁺ concentration).

From a practical point of view, the authors support the idea that both HIIT and CR must be part of training programs for endurance runners to maximize adaptations to training. Additionally, the authors suggest that the inclusion of 2 to 3 HIIT sessions in a running plan, accumulating work periods longer than 10 min and working at close to or above vVO2max per session, lets recreational endurance runners improve their athletic performance. But what type of HIIT? In general, a good practice for endurance runners would include HIIT protocols involving short work periods (<1 min) with work–rest ratios of approximately 1:1 to 1:2, performed at close to all-out intensities, which enable athletes to elicit similar or greater mean average VO2 and to train at an increased running pace (above 100%VO2max) when compared with longer HIIT or CR protocols. Nevertheless, the authors highlight that although HIIT and SIT, together with CR, must be a part of running plans for endurance athletes, the HIIT-based workload will vary according to training periodization, which must be based on the progressive overload principle.

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Authors’ contributions

FGP revised literature and drafted the manuscript; VMSH critically revised the manuscript; PALR revised literature and helped to draft the manuscript. All authors have read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

Competing interests

None of the authors declare competing financial interests.

References

1. Laursen PB. Training for intense exercise performance: high-intensity or high-volume training? Scand J Med Sci Sports 2010;20(Suppl. 2):S1–10.
2. Laursen PB, Jenkins DG. The scientific basis for high-intensity interval training optimising training programmes and maximising performance in highly trained endurance athletes. Sports Med 2002;32:53–73.
3. Tschakert G, Hofmann P. High-intensity intermittent exercise: methodological and physiological aspects. Int J Sports Physiol Perform 2013;8:600–10.
4. Buchheit M, Laursen PB. High-intensity interval training, solutions to the programming puzzle. Part II: anaerobic energy, neuromuscular load and practical applications. Sports Med 2013;43:927–54.
5. Buchheit M, Laursen PB. High-intensity interval training, solutions to the programming puzzle: part I: cardiopulmonary emphasis. Sports Med 2013;43:313–38.
6. Esteve-Lanajo J, San Juan AF, Earnest CP, Foster C, Lucia A. How do endurance runners actually train? Relationship with competition performance. Med Sci Sports Exerc 2005;37:496–504.
7. Billat LV. Interval training for performance: a scientific and empirical practice. Special recommendations for middle- and long-distance running. Part I: aerobic interval training. Sports Med 2001;31:13–31.
8. Billat LV. Interval training for performance: a scientific and empirical practice. Special recommendations for middle- and long-distance running. Part II: anaerobic interval training. Sports Med 2001;31:75–90.
9. Billat V, Lepretre PM, Hugas AM, Laurence MH, Salim D, Koralsztein JP. Training and bioenergetic characteristics in elite male and female Kenyan runners. Med Sci Sports Exerc 2003;35:297–304.
10. Girard O, Mendez-Villanueva A, Bishop D. Repeated-sprint ability—part I: factors contributing to fatigue. Sports Med 2011;41:673–94.
11. Bishop D, Girard O, Mendez-Villanueva A. Repeated-sprint ability—part II: recommendations for training. Sports Med 2011;41:741–56.
12. Gist NH, Fedewa MV, Dishman RK, Curren KJ. Sprint interval training effects on aerobic capacity: a systematic review and meta-analysis. Sports Med 2014;44:269–79.
13. Sloth M, Sloth D, Overgaard K, Dalgas U. Effects of sprint interval training on VO2max and aerobic exercise performance: a systematic review and meta-analysis. Scand J Med Sci Sports 2013;23:e341–52.
14. Bishop DJ. Fatigue during intermittent-sprint exercise. Clin Exp Pharmacol Physiol 2012;39:836–41.
15. Boutcher SH. High-intensity intermittent exercise and fat loss. J Obes 2011;2011:868305. doi:10.1155/2011/868305
16. Iaia FM, Bangsbo J. Speed endurance training is a powerful stimulus for physiological adaptations and performance improvements of athletes. Scand J Med Sci Sports 2010;20(Suppl. 2):S11–23.
17. Skof B, Strojnik V. Neuromuscular fatigue and recovery dynamics following prolonged continuous run at anaerobic threshold. Br J Sports Med 2006;40:219–22.
18. Millet GY, Lepers R. Alterations of neuromuscular function after prolonged running, cycling and skiing exercises. Sports Med 2004;34:105–16.
19. Higashihara A, Ono T, Kubota J, Okuwaki T, Fukubayashi T. Functional differences in the activity of the hamstring muscles with increasing running speed. J Sports Sci 2010;28:1085–92.
20. O’Brien BJ, Wibskov J, KnezeWL, Paton CD, Harvey JT. The effects of interval-exercise duration and intensity on oxygen consumption during treadmill running. J Sci Med Sport 2008;11:287–90.
21. Kaakinen P, Hynynen E, Mann T, Rusko H, Nummela A. Heart rate variability is related to training load variables in interval running exercises. Eur J Appl Physiol 2012;112:829–38.
22. Seiler S, Hrelia KD. The impact of rest duration on work intensity and RPE during interval training. Med Sci Sports Exerc 2005;37:1601–7.
23. Vuorima T, Vasankari T, Rusko H. Comparison of physiological strain and muscular performance of athletes during two intermittent running exercises at the velocity associated with VO2max. Int J Sports Med 2000;21:96–101.
24. Billat VL, Slawinski J, Bocquet V, Chassaing P, Demarle A, Koralsztein JP. Very short (15s-15s) interval-training around the critical velocity allows middle-aged runners to maintain VO2max for 14 minutes. Int J Sports Med 2001;22:201–8.
25. Wallner D, Simi H, Tschakert G, Hofmann P. Acute physiological response to aerobic short-interval training in trained runners. Int J Sports Physiol Perform 2014;9:661–6.
26. Seiler S, Sjaersen JE. Effect of work duration on physiological and rating scale of perceived exertion responses during self-paced interval training. Scand J Med Sci Sports 2004;14:318–25.
27. van Gent RN, Siem D, van Middelkoop M, van Os AG, Bierma-Zeinstra SMA, Koes BW. Incidence and determinants of lower extremity running injuries in long distance runners: a systematic review. Br J Sports Med 2007;41:469–80.
28. Fields KB, Sykes JC, Walker KM, Jackson JC. Prevention of running injuries. Curr Sports Med Rep 2010;9:176–82.
29. Nielsen RO, Buist I, Sørensen H, Lind M, Rasmussen S. Training errors and running related injuries: a systematic review. Int J Sports Phys Ther 2012;7:58–75.
30. Downs SH, Black N. The feasibility of creating a checklist for the assessment of the methodological quality both of randomised and non-randomised studies of health care interventions. J Epidemiol Community Health 1998;52:377–84.
31. Maher CG, Sherrington C, Herbert RD, Moseley AM, Elkins M. Reliability of the PEDro scale for rating quality of randomized controlled trials. Phys Ther 2003;83:713–21.
32. Vezzoli A, Pugliese L, Marzorati M, Serpiello FR, La Torre A, Porcelli S. Time-course changes of oxidative stress response to high-intensity discontinuous training versus moderate-intensity continuous training in masters runners. PLoS One 2014;9:e87506. doi:10.1371/journal.pone.0087506.
33. Bangsbo J, Gunnarsson TP, Wendell J, Nybo L, Thomassen M. Reduced volume and increased training intensity elevate muscle Na+–K+ pump alpha2-subunit expression as well as short- and long-term work capacity in humans. J Appl Physiol 2009;107:1771–80.
34. Gunnarsson TP, Bangsbo J. The 10-20-30 training concept improves performance and health profile in moderately trained runners. J Appl Physiol 2012;113:16–24.
35. Glemann L, Gunnarsson TP, Hellsten Y. Bangsbo J. 10-20-30 training increases performance and lowers blood pressure and VEGF in runners. Scand J Med Sci Sports 2015;25:479–89.
36. Denadai BS, Ortiz MJ, Greco CC, de Mello MT. Interval training at 95% and 100% of the velocity at VO2max: effects on aerobic physiological indexes and running performance. Appl Physiol Nutr Metab 2006;31:737–43.
37. Esfarjani F, Laursen PB. Manipulating high-intensity interval training: effects on the lactate threshold and 3000 m running performance in moderately trained males. J Sci Med Sport 2007;10:27–35.
38. Smith TP, Coombes JS, Geraghty DP. Optimising high-intensity treadmill training using the running speed at maximal O2 uptake and the time for which this can be maintained. Eur J Appl Physiol 2003;90:337–43.
39. Zator M, Michalik K. Effects of interval training-based glycolytic capacity on physical fitness in recreational long-distance runners. Hum Mov 2015;16:71–7.
40. Tanner AV, Nielsen BV, Allgrove J. Salivary and plasma cortisol and testosterone responses to interval and tempo runs and a bodyweight-only circuit session in endurance-trained men. J Sports Sci 2014;32:680–9.
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41. Latorre-Román PÁ, García-Pinillos F, Martínez-López EJ, Soto-Hermo VM. Concurrent fatigue and postactivation potentiation during extended interval training in distance runners. *Mot Educ Fisica* 2014;20:423–30.

42. García-Pinillos F, Soto-Hermo VM, Latorre-Román PA. Acute effects of extended interval training on countermovement jump and handgrip strength performance in endurance athletes: postactivation potentiation. *J Strength Cond Res* 2015;29:11–21.

43. Hernández-Torres RP, Ramos-Jiménez A, Torres-Durán PV, Romero-González J, Mascher D, Posadas-Romero C, et al. Effects of single sessions of low-intensity continuous and moderate-intensity intermittent exercise on blood lipids in the same endurance runners. *J Sci Med Sport* 2009;12:323–31.

44. Demarie S, Koralztsen JP, Billat V. Time limit and time at VO2max during a continuous and an intermittent run. *J Sports Med Phys Fitness* 2000;40:96–102.

45. Collins MH, Pearsall DJ, Zavorsky GS, Bateni H, Turcotte RA, Montgomery DL. Acute effects of intense interval training on running mechanics. *J Sports Sci* 2000;18:83–90.

46. Millet GP, Libicz S, Borrani F, Fattori P, Bignet F, Candau R. Effects of increased intensity of intermittent training in runners with differing VO2 kinetics. *Eur J Appl Physiol* 2003;90:50–7.

47. García-Pinillos F, Párraga-Montilla JA, Soto-Hermo VM, Latorre-Román PA. Changes in balance ability, power output, and stretch-shortening cycle utilization after two high-intensity intermittent training protocols in endurance runners. *J Sport Health Sci* 2016;5:430–6.

48. Laffite LP, Mille-Hamard L, Koralztsen JP, Billat VL. The effects of interval training on oxygen pulse and performance in supra-threshold runs. *Arch Physiol Biochem* 2003;111:202–10.

49. Hamada T, Sale DG, Macdougall JD. Postactivation potentiation in endurance-trained male athletes. *Med Sci Sports Exerc* 2000;32:403–11.

50. Nicol C, Komi PV, Marconnet P. Fatigue effects of marathon running on neuromuscular performance. *Scand J Med Sci Sports* 2007;1:10–7.

51. Vuorimaa T, Virlander R, Kurkihiha T, Vasankari T, Häkkinen K. Acute changes in muscle activation and leg extension performance after different running exercises in elite long distance runners. *Eur J Appl Physiol* 2006;96:282–91.

52. Benson LC, O’Connor KM. The effect of exertion on joint kinematics and kinetics during running using a waveform analysis approach. *J Appl Biomech* 2015;31:250–7.

53. Hanley B, Mohan AK. Changes in gait during constant pace treadmill running. *J Strength Cond Res* 2014;28:1219–25.

54. Mizrahi J. Effect of fatigue on leg kinematics and impact acceleration in long distance running. *Hum Mov Sci* 2000;19:139–51.

55. Derrick TR, Derru D, McLean SP. Impacts and kinematic adjustments during an exhaustive run. *Med Sci Sports Exerc* 2002;34:998–1002.

56. Abt J, Sell T, Chu Y, Lovalekar M, Burdett R, Lephart S. Running kinematics and shock absorption do not change after brief exhaustive running. *J Strength Cond Res* 2011;25:1479–85.

57. Latorre-Román PÁ, Jiménez MM, Hermoso VMS, Sánchez JS, Molina AM, Fuentes AR, et al. Acute effect of a long-distance road competition on foot strike patterns, inversion and kinematics parameters in endurance runners. *Int J Perform Anal Sport* 2015;15:588–97.

58. Larson P, Higgins E, Kaminski J, Decker T, Preble J, Lyons D, et al. Foot strike patterns of recreational and sub-elite runners in a long-distance road race. *J Sports Sci* 2011;29:1665–73.

59. Koblbauer IF, van Schooten KS, Verhagen EA, van Dieën JH. Kinematic changes during running-induced fatigue and relations with core endurance in novice runners. *J Sci Med Sport* 2014;17:419–24.

60. Dierks TA, Davis IS, Hamill J. The effects of running in an exerted state on lower extremity kinematics and joint timing. *J Biomech* 2010;43:2993–8.

61. Castro A, LaRoche DP, Fraga CHW, Gonçalves M. Relationship between running intensity, muscle activation, and stride kinematics during an incremental protocol. *Sci Sports* 2013;28:e85–92.

62. Schache AG, Blanch PD, Rath DA, Wrigley TV, Starr R, Bennell KL. A comparison of overground and treadmill running for measuring the three-dimensional kinematics of the lumbo-pelvic–hip complex. *Clin Biomech (Bristol, Avon)* 2001;16:667–80.

63. García-Pérez JA, Pérez-Soriano P, Llana S, Martínez-Nova A, Sánchez-Zuriaga D. Effect of overground vs treadmill running on plantar pressure: influence of fatigue. *Gait Posture* 2013;38:929–33.

64. Schubert AG, Kempf J, Heiderscheit BC. Influence of stride frequency and length on running mechanics: a systematic review. *Sports Health* 2014;6:210–7.

65. Saunders PU, Pyne DB, Telford RD, Hawley JA. Factors affecting running economy in trained distance runners. *Sports Med* 2004;34:465–85.

66. Nummelä AT, Paavolainen LM, Sharwood KA, Lambert MI, Noakes TD, Rusko HK. Neuromuscular factors determining 5 km running performance and running economy in well-trained athletes. *Eur J Appl Physiol* 2006;97:1–8.

67. Joyner MJ, Coyle EF. Endurance exercise performance: the physiology of champions. *J Physiol* 2008;586:35–44.