Abstract
High-intensity interval training (HIIT) refers to exercise that is characterized by relatively short bursts of vigorous activity, interspersed by periods of rest or low-intensity exercise for recovery. In untrained and recreationally active individuals, short-term HIIT is a potent stimulus to induce physiological remodeling similar to traditional endurance training despite a markedly lower total exercise volume and training time commitment. As little as six sessions of ‘all-out’ HIIT over 14 days, totaling ~15 min of intense cycle exercise within total training time commitment of ~2.5 h, is sufficient to enhance exercise capacity and improve skeletal muscle oxidative capacity. From an athletic standpoint, HIIT is also an effective strategy to improve performance when supplemented into the already high training volumes of well-trained endurance athletes, although the underlying mechanisms are likely different compared to less trained subjects. Most studies in this regard have examined the effect of replacing a portion (typically ~15–25%) of base/normal training with HIIT (usually 2–3 sessions per week for 4–8 weeks). It has been proposed that a polarized approach to training, in which ~75% of total training volume be performed at low intensities, with 10–15% performed at very high intensities may be the optimal training intensity distribution for elite athletes who compete in intense endurance events.

Introduction
High-intensity interval training (HIIT) refers to exercise that is characterized by relatively short bursts of vigorous activity, interspersed by periods of rest or low-intensity exercise for recovery. HIIT is almost infinitely variable, and the
specific physiological adaptations induced by this form of training are likely determined by many factors including the mode and precise nature of the exercise stimulus, i.e. the intensity, duration and number of intervals performed, as well as the duration and activity patterns during recovery. In untrained and recreationally active individuals, short-term HIIT is a potent stimulus to induce physiological remodeling similar to traditional endurance training despite a markedly lower total exercise volume and training time commitment [1–3]. These findings are noteworthy from a public health perspective, given that ‘lack of time’ remains one of the most commonly cited barriers to regular exercise participation [4]. From an athletic standpoint, HIIT is also an effective strategy to improve performance when supplemented into the already high training volumes of well-trained endurance athletes [5–9]. This brief review considers some of the mechanisms responsible for enhanced aerobic energy provision after low-volume HIIT, although this work is based largely on studies conducted on untrained or recreationally active individuals. The other focus is the practical application of HIIT to improve athletic performance, recognizing that the underlying mechanisms are likely different compared to less trained subjects.

Adaptations to Low-Volume HIIT in Untrained and Recreationally Active Individuals

The most common model employed in low-volume HIIT studies has been the Wingate Test, which consists of 30 s of ‘all-out’ cycling on a specialized ergometer [10]. Mean power output generated during a Wingate Test is very high and typically corresponds to a value that is ~2–3 times greater than achieved at the end of a standard maximal oxygen uptake (VO₂max) test. Wingate-based HIIT typically consists of 4–6 work bouts separated by a few minutes of recovery, for a total of 2–3 min of intense exercise spread over a training session that lasts ~20 min. As little as six sessions of this type of training over 14 days, totaling ~15 min of all-out cycle exercise within total training time commitment of ~2.5 h, is sufficient to dramatically improve exercise capacity in untrained and recreationally active individuals. For example, Burgomaster et al. [11] showed that subjects doubled the length of time that exercise could be maintained at a fixed submaximal workload – from ~26 to 51 min during cycling at 80% of pre-training VO₂max – after only 2 weeks of HIIT. Other work has shown that a similar period of HIIT improved performance during tasks that more closely resemble normal athletic competition, including laboratory time trials that simulated cycling races lasting from ~2 min to ~1 h [2, 12].
With respect to physiological adaptations, as little as 6 sessions of Wingate-based HIIT over 2 weeks is a potent stimulus to enhance skeletal muscle oxidative capacity, as reflected by the maximal activity and/or protein content of mitochondrial enzymes [2, 11]. We have also directly compared responses to 6 weeks of Wingate-based HIIT versus a much higher volume of continuous moderate-intensity endurance training that was designed according to current public health guidelines [1, 13]. These studies revealed similar training-induced improvements in VO₂max and various markers of skeletal muscle and cardiovascular adaptation despite large differences in weekly training volume (~90% lower in the HIIT group) and time commitment (~67% lower in the HIIT group). In addition to an increased skeletal muscle oxidative capacity [1] and enhanced peripheral vascular structure and function [13], other endurance-related adaptations that are apparent after several weeks of Wingate-based HIIT include a reduced rate of glycogen utilization and lactate production during matched-work exercise, an increased capacity for whole-body and skeletal muscle lipid oxidation and increased muscle content of metabolic transport proteins [1, 2, 11, 12].

Some of these physiological adaptations may well have been responsible for the faster O₂ uptake kinetics during exercise reported following HIIT [14, 15]. In the study by Bailey et al. [14], 24 recreationally active subjects were divided into three groups: a control group which completed no additional exercise training; a HIIT group which completed six sessions of 4–7 × 30-second Wingate sprints, and an endurance training group which completed six sessions of work-matched, moderate-intensity cycling. All subjects completed moderate-intensity and high-intensity 'step' exercise transitions before and after the 2-week intervention period. Following HIIT, the phase 2 VO₂ kinetics was significantly speeded by 20–25% for both moderate-intensity and severe-intensity exercise, and the amplitude of the VO₂ slow component, which reflects a progressive loss of metabolic stability during high-intensity exercise, was significantly reduced. Moreover, following HIIT, the time to exhaustion during high-intensity exercise was improved by 53% (from 700 ± 234 to 1,074 ± 431 s). Neither VO₂ kinetics nor performance was significantly altered in the control group or the endurance training group. Interestingly, the improved VO₂ kinetics in the HIIT group was associated with changes in the muscle deoxygenation signal, measured with near infra-red spectroscopy, which suggested that muscle fractional O₂ extraction was enhanced. The improvement in VO₂ kinetics following HIIT likely reflects physiological adaptations to the training which improved muscle blood flow and its distribution as well as muscle metabolic control [16].

Wingate-based training is very potent; however, low-volume HIIT does not have to be ‘all out’ in order to be effective. Recently, a model was proposed that
might be more ‘practical’, in that it does not require a specialized ergometer and may have wider application to different populations including people at risk for cardiometabolic disorders [17]. The protocol consists of $10 \times 60$-second work bouts at a constant-load intensity that elicits $\sim 90\%$ of maximal heart rate, interspersed with 60 s of recovery. The method is still time efficient in that only 10 min of exercise is performed over a 20-min training session. Importantly, the model is also effective at inducing rapid skeletal muscle remodeling towards a more oxidative phenotype [17], similar to previous Wingate-based HIIT studies and high-volume endurance training [1]. We also showed in a small pilot study that the protocol was well tolerated by patients with type 2 diabetes, and 6 sessions over 2 weeks was sufficient to reduce average 24-hour blood glucose concentration, measured via continuous glucose monitoring under standardized diet but otherwise free-living conditions [18]. These beneficial adaptations were realized even though the weekly training time commitment was much lower than common public health guidelines that generally call for at least 150 min of moderate to vigorous exercise per week to promote health.

Recently, Gunnarsson and Bangsbo [19] investigated the physiological effect of an alteration from standard endurance training to interval training on indicators of cardiovascular health, muscle metabolism, VO$_2$max and performance in moderately trained runners. The subjects were divided into a high-intensity training group and a control group which continued with normal training. For a 7-week intervention period, the interval training group replaced all training sessions with low-, moderate-, and high-speed running ($<30$, $<60$, and $>90\%$ of maximal intensity) for 30, 20, and 10 s, respectively, in three or four 5-min blocks interspersed by 2 min of recovery. In this way, training volume was reduced from approximately 30 to 14 km of running per week. After the intervention period, VO$_2$max in the interval training group was increased by 4%, and performance in a 1,500-meter and a 5-km run improved significantly (by 21 and 48 s, respectively). Moreover, systolic blood pressure was reduced and total and low-density lipoprotein cholesterol were significantly lower. No alterations were observed in CON across the intervention period. Interestingly, muscle membrane proteins and enzyme activity did not change in either of the groups. This study reveals another type of HIIT that can improve both the cardiovascular health profile and exercise performance. Specifically, interval training involving 10-second near-maximal bouts can improve performance despite a $\sim 50\%$ reduction in training volume.

Anecdotally, patients prefer to complete HIIT sessions than longer bouts of low-intensity exercise. Because HIIT accelerates the adaptation to training, this may provide patient or sedentary populations of low fitness with early encouragement which may translate into improved adherence to a longer-term train-
High-Intensity Interval Training 55

ing program. HIIT may be especially beneficial early in a training intervention in such populations, and may be supplemented with traditional aerobic training later on to maximize training adaptations. Another advantage of HIIT is that, unlike traditional endurance training, it provides almost infinite variety, with the number, duration and intensity of each of the work bouts being adjustable, along with the duration and intensity of the recovery intervals. This may enable interest to be maintained over the longer-term. In summary, in previously untrained or recreationally active individuals, low-volume HIIT is a time-efficient strategy to rapidly improve exercise capacity and stimulate numerous physiological adaptations that are normally associated with traditional endurance training.

It is interesting to consider the adaptations to HIIT in light of the determinants of endurance performance put forward in the well-established model of Ed Coyle [20]. This model proposes that endurance performance is chiefly a function of the VO₂max, efficiency during submaximal exercise (which is more commonly termed economy during running), and the fractional utilization of the VO₂max. The former is important because the performance VO₂ clearly cannot exceed the VO₂max; efficiency is important because it determines the performance speed corresponding to a given VO₂, and fractional utilization is important because it dictates the VO₂ that can be sustained for a given distance or exercise duration. While longer term HIIT may invoke central cardiovascular adaptations which underpin an increased VO₂max, it appears, at least in the short term, that HIIT mainly stimulates peripheral muscle metabolic adaptations [3]. In terms of Coyle’s model [20], HIIT-induced improvements in substrate utilization and oxidative energy turnover may therefore enhance endurance capacity by increasing the fractional utilization of the VO₂max. Also, although not reported explicitly, we have noticed in several studies that even short-term HIIT consistently results in a small but significant reduction in the O₂ cost of submaximal exercise, which may be evidence of improved efficiency.

Effect of HIIT in Highly Trained Individuals

In comparison to untrained and recreationally active subjects, much less is known about the response of highly trained individuals to HIIT. Although typically an integral component of training programs for the enhancement of athletic performance, research into the unique effects of HIIT on the performance of well-trained individuals is sparse [5]. As noted by Hawley et al. [5], there are various reasons for this including the fact that sports scientists have found it difficult to persuade elite athletes to experiment with their training regimes. In-
deed, scientists themselves have urged caution in giving training recommendations to athletes and coaches based on the relatively limited literature available [21]. Nonetheless, there is evidence to suggest that inserting a relatively short period of HIIT into the already high training volumes of well-trained athletes can further enhance performance [5–9]. Most studies in this regard have examined the effect of replacing a portion (typically ~15–25%) of base/normal training with HIIT (usually 2–3 sessions per week for 4–8 weeks). Improvements in performance with this approach have generally been interpreted to be due to the inclusion of the HIIT, although it is possible that the reduced training volume per se also contributes to some degree. The precise nature of the HIIT stimulus has varied from repeated intervals lasting up to 5 min at an intensity eliciting ~80% VO₂max to 30-second efforts at an all-out pace or power outputs corresponding to ≥175% of VO₂max.

One of the first studies to demonstrate the beneficial effect of HIIT on performance in trained subjects was conducted by Acevedo and Goldfarb [22]. These authors examined the effect of 8 weeks of increased training intensity in 7 competitive male distance runners. Training intensity was increased on 3 days per week by having subjects perform intervals at 90–95% of maximal heart rate or Fartlek style workouts, whereas they maintained their habitual continuous runs on the other days of the week. 10-km race time improved after the intervention by over 1 min from 35:27 to 34:24, despite no change in VO₂max. Other investigators have subsequently reported performance improvements when trained runners reduced their total training volume but increased intensity through the addition of brief all-out HIIT efforts [23]. For a 6- to 9-week period, Bangsbo et al. [23] assigned runners to a group that replaced approximately one quarter of their normal training volume with 12 × 30-second all-out sprint runs 3–4 times per week, or a group that continued with their normal endurance training (~55 km/week). VO₂max was not altered; however, the HIIT intervention improved 3 km (from 10.4 to 10.1 min) and 10 km run time (from 37.3 to 36.3 min), whereas the control group showed no change in performance. Similarly, Smith et al. [24] reported that trained runners who completed 4 weeks of HIIT (consisting of 6 × ~2 min at VO₂max running speed, 2×/week) improved 3-km run performance compared to a group that continued with their normal training.

Researchers in South Africa conducted a series of studies in the 1990s that examined the effect of HIIT in well-trained competitive cyclists [25–28]. The subjects in these studies were all men with a training history of at least 3–4 years who were cycling at ~300 km/week, but had not undertaken any interval training for several months before investigation. They typically presented with VO₂max values ≥65 ml/kg per min and peak sustained power outputs >400 W, confirming
their highly trained state [reviewed in 5]. Lindsay et al. [25] examined the effect of replacing 15% of the cyclists’ normal base training with interval training, which consisted of 6–8 repetitions × 5 min at an intensity that elicited 80% of each subject’s peak power output (PPO), interspersed with 60 s of recovery. After 6 sessions of HIIT over a 4 weeks’ period, the cyclists improved their peak power and speed during a 40-km time trial that translated into improved performance (56.4 vs. 54.4 min). Stepto et al. [26] investigated the effect of varying the intensity and duration of a 3-week (6 sessions) HIIT stimulus on 40-km time trial performance. Twenty well-trained cyclists were randomly assigned to one of five types of interval-training session: 12 × 30 s at 175% PPO, 12 × 60 s at 100% PPO, 12 × 2 min at 90% PPO, 8 × 4 min at 85% PPO, or 4 × 8 min at 80% PPO. As the authors hypothesized, training sessions that employed work bouts that were closely matched to race pace (8 × 4 min at 85% PPO) significantly enhanced performance (2.8%, 95% CI: 4.3–1.3%). Somewhat surprisingly, the short duration, supra-maximal work bouts (12 × 30 s at 175% of PPO) were just as effective in improving performance (2.4%, 95% CI: 4.0–0.7%), whereas the other interval protocols did not produce statistically significant improvements in performance. However, the sample size in each group was small (n = 4), and Laursen et al. [29] have subsequently reported that 40-km time trial performance is improved in trained cyclists after a 4-week HIIT protocol that consists of 8 × ∼2.5 bouts per session at an intensity equivalent to 100% PPO.

The mechanisms responsible for the observed performance improvements after HIIT in highly trained individuals are likely different compared to less trained subjects. Whereas rapid increases in skeletal muscle oxidative capacity are observed after a short period of low-volume HIIT in untrained and recreationally active subjects [2, 11, 12, 17], several weeks of HIIT does not further increase the maximal activity of mitochondrial enzymes in highly trained individuals [27, 28]. HIIT has been reported to improve skeletal muscle buffering capacity in highly trained subjects, and it has also been suggested that training-induced changes in Na⁺/K⁺ pump activity may help to preserve cell excitability and force production, thereby delay fatigue development during intense exercise [8].

It has been proposed that a polarized approach to training, in which ∼75% of total training volume be performed at low intensities, with 10–15% performed at very high intensities may be the optimal training intensity distribution for elite athletes who compete in intense endurance events [9]. While it is clear that many athletes do adopt this approach, there are also examples of highly accomplished athletes who complete their continuous ‘steady-state’ training at relatively high intensities and who include sustained ‘tempo’ training sessions in their weekly program [30]. It would therefore seem appropriate for athletes to
use a variety of approaches, in a carefully balanced selection of training sessions across the intensity-duration continuum, to optimize the stimuli for physiological adaptation. By activating both the adenosine monophosphate kinase and calcium-calmodulin kinase signaling pathways, this may provide a potent stimulus to the so-called ‘master switch’, peroxisome proliferator-activated receptor-
g coactivator-1α, which in turn may lead to a variety of adaptations likely to enhance endurance exercise performance.

Although inserting a relatively short period of HIIT into the high training volumes of well-trained athletes can further enhance performance \[5–9\], it is unlikely that this approach is sustainable in the longer-term. It is feasible that such training, if undertaken continuously, could result in overtraining. Therefore, it is recommended that HIIT be used periodically as an additional stimulus to adaptation, perhaps every 8–10 weeks and/or in the taper period prior to a major competition.

Little is known regarding the potential for nutrition or other interventions to augment physiological and performance effects of HIIT in elite athletes. For example, it is feasible that performing HIIT in hypoxia might further increase the signaling which results in enhanced angiogenesis or mitochondrial biogenesis. However, one study found short-term hypoxic exposure did not elicit a greater increase in performance or hematological modifications compared to HIIT alone in well-trained cyclists and triathletes \[31\]. Several nutritional ergogenic aids including caffeine, creatine, nitrate, sodium bicarbonate and β-alanine, alone or in combination, during HIIT could theoretically facilitate training quality acutely and thus result in an improved training outcome. In this regard, Edge et al. \[32\] reported that subjects who ingested sodium bicarbonate over an 8-week high-intensity intermittent cycle training program, matched for total volume, experienced greater improvements in time trial performance compared to a placebo group. Another interesting question is whether the potent effects of HIIT on physiological adaptations and performance are linked more to the absolute intensity achieved in each of the work bouts or simply to the repeated transient metabolic challenges inherent to interval training. The absolute intensity of the work bout will dictate the motor unit recruitment profile. It is possible that HIIT is effective, at least in part, because it activates and thus enhances the metabolic profile of the type 2 fibers that are positioned higher in the recruitment hierarchy. Alternatively or additionally, the repeated metabolic perturbations (rapid changes in the concentrations of ATP, ADP, Pi, PCr, etc.) in the abrupt transitions from rest to exercise may be important in evoking the cellular adaptations known to occur following HIIT. Further research is required to investigate these important questions.
Conclusion

In untrained and recreationally active individuals, short-term HIIT is a potent stimulus to induce physiological adaptations similar to traditional endurance training. As little as six sessions of ‘all-out’ HIIT over 14 days, totaling ~15 min of intense cycle exercise, is sufficient to enhance skeletal muscle oxidative capacity and exercise endurance. HIIT is also an effective strategy to improve performance when it replaces some of the high training volume in the programs of well-trained endurance athletes, although the specific mechanisms may be different compared to less trained individuals. It has been proposed that a polarized approach to training, in which ~75% of total training volume be performed at low intensities, with 10–15% performed at very high intensities may be the optimal training intensity distribution for elite athletes who compete in intense endurance events.

Disclosure Statement

The authors declare that no financial or other conflict of interest exists in relation to the content of the chapter.

References


24 Smith TP, Coombes JS, Geraghty DP: Optimising high-intensity training using the running speed at maximal O₂ uptake and the time for which this can be maintained. Eur J Appl Physiol 2003;89:337–343.


