It's about the long game, not epic workouts: unpacking HIIT for endurance athletes

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Perspective

It's about the long game, not epic workouts: unpacking HIIT for endurance athletes

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Abstract

High-intensity interval training (HIIT) prescriptions manipulate intensity, duration, and recovery variables in multiple combinations. Researchers often compare different HIIT variable combinations and treat HIIT prescription as a "maximization problem", seeking to identify the prescription(s) that induce the largest acute VO_2/HR/RPE response. However, studies connecting the magnitude of specific acute HIIT response variables like work time >90% of VO_2max and resulting cellular signalling and/or translation to protein upregulation and performance enhancement are lacking. This is also not how successful endurance athletes train. First, HIIT training cannot be seen in isolation. Successful endurance athletes perform most of their training volume below the first lactate turn point (<LT1), with "threshold training" and HIIT as integrated parts of a synergistic combination of training intensities and durations. Second, molecular signalling research reveals multiple, "overlapping" signalling pathways driving peripheral adaptations, with those pathways most sensitive to work intensity showing substantial feedback inhibition. This makes current training content and longer-term training history critical modulators of HIIT adaptive responses. Third, long term maximization of endurance capacity extends over years. Successful endurance athletes balance low-intensity and high-intensity, low systemic stress, and high systemic stress training sessions over time. The endurance training process is therefore an "optimization problem". Effective HIIT sessions generate both cellular signal and systemic stress that each individual athlete responds to and recovers from over weeks, months, and even years of training. It is not "epic" HIIT sessions but effective integration of intensity, duration, and frequency of all training stimuli over time that drives endurance performance success.

Key words: interval training, endurance athletes, exercise intensity, stress responses, molecular signalling, training monitoring

My context for studying HIIT

Metabolically, we can define high-intensity interval training (HIIT) as intermittent exercise with work bouts and overall workouts performed in the *severe* intensity zone at a power output or velocity between the second lactate turn point (LT2) or second ventilatory threshold (VT2) and maximal oxygen consumption (VO_2max) (Gaesser and Poole 1996; Billat 2001; Pringle et al. 2003; Rosenblat et al. 2020). In the important context of health promotion and fitness improvement in recreational exercisers, HIIT has been described as "*a convenient and time efficient exercise modality consisting of short bouts of high-intensity work, separated by appropriate recovery periods*" (Edwards et al. 2023). "Convenient" is probably not the first word well-trained athletes think of when describing their HIIT training sessions. Their HIIT sessions are highly demanding, both perceptually and physiologically. The HIIT prescriptions performed by these athletes will often greatly exceed in intensity and total duration those that successfully induce positive adaptations and health benefits in untrained and moderately trained people. To paraphrase 3-time Tour de France winner Greg Lemond, HIIT always hurts, but with time and training, we just go faster! HIIT is a fundamental and seemingly obligatory component of the training of successful endurance athletes across disciplines and race durations (Seiler 2010; Tønnessen et al. 2014). HIIT sessions are often key anchor points in the weekly training plan and serve as objective benchmarks of capacity development over time for athletes and recreational exercisers alike. Regular HIIT is engrained in the training culture in all endurance sports and included in the research portfolio of many sport scientists. My arguments in this viewpoint article are presented in the context of balancing the demonstrably positive as well as the potentially negative impact of long-term integration of HIIT by already well-trained endurance athletes and exercisers. I will first present my views on HIIT programming (Section 1), then the training monitoring process (Section 2), and finally, attempt to understand the role of HIIT in the overall mosaic of adaptive molecular signalling and physiological adaptation (Section 3).

Section 1: HIIT programming

HIIT's place in the overall training intensity distribution of endurance athletes

HIIT as a training stimulus should not be viewed in isolation but understood within the framework of the total training load and intensity distribution. There is good systematic evidence that a well-executed mesocycle of "almost any HIIT prescription" improves VO_2max and endurance performance modestly compared to only performing a substantial volume of low-intensity training (LIT, ≤LT1, e.g., Seiler et al. 2011; Stepto et al. 1999; Rosenblat et al. 2023). The interaction between intensity and duration generates both acute stimuli and aggregative molecular signals for long-term adaptation. About 80% of the training sessions performed by endurance athletes competing over durations from 4 min to >4 h are performed at an intensity below the first lactate turn point, LT1 (i.e., Seiler 2010; Steggall and Sperlich 2015; Haugen et al. 2021; Haugen et al. 2022). Paradoxically, it seems that about 80% of the published laboratory studies on endurance athletes focus on the upper 20% of their training intensity distribution. The ecological validity of most HIIT research is weakened by the disconnect between practically achievable laboratory intervention timeframes spanning 2–12 weeks of training (usually ∼4–8 weeks), and the 52-week annual cycles and multiple years endurance athletes train, race, and develop across (e.g., Staff et al. 2023). For example, a Norwegian national team coach of cross-country (XC) skiers in Norway explained that a simple but predictive rule-of-thumb for seasonal success among their male and female elite XC skiers was to complete ∼100 "hard" sessions (including "threshold", HIIT, and races) during a season, out of ∼500 total endurance sessions and races. In this holistic and real-world context, coaches and athletes are not pursuing "maximal time near VO_2 max" (e.g., Billat et al. 2000; Jones et al. 2008; Bailey et al. 2011; Zadow et al. 2015; Bossi et al. 2020; Rønnestad et al. 2020) nor an otherwise "maximally exhaustive" HIIT session in isolation. Instead, they pursue an individually sustainable integration of a high overall training volume and regular, specific stimuli above LT1 (including but not limited to HIIT) across typical training weeks, periodized multi-week macrocycle progressions, annual cycles, or an Olympic quadrennium. I find no evidence in my own research, the research of other excellent sport scientists, or most convincingly, the long-term practice of successful endurance athletes, to support the current existence or future discovery of any single "optimal" HIIT prescription or regime, even if the possibility is tantalizing. Why not? I will start my viewpoint on this question by unpacking the HIIT prescription.

The algebra and effort within HIIT programming variables

The how often, how hard, and how long of endurance training is encapsulated in *frequency*, *intensity*, and *duration*. The distribution of training time (e.g., HR based time-in-zone) or training sessions (i.e., a "session goal" categorical approach) can be determined using various intensity zone schemes (e.g., Seiler 2010; Sylta et al. 2014; Seiler and Sylta 2017; Haugen et al. 2022). Intensity and duration are also incorporated into any HIIT prescription, and these prescriptions can become quite detailed (e.g., Bucheit and Laursen 2013). I will condense the prescription to its most physiologically impactful elements that: (1) partially uncouple cardiovascular and peripheral loading and (2) induce both adaptive cellular signalling and (potentially maladaptive) systemic stress. These are: (1) work bout duration, the duration of each "hard" work period in the HIIT prescription, (2) accumulated work duration, the summated duration of all completed work bouts (accumulated work duration (AWD)), and (3) average work bout intensity. A fourth variable, the recovery duration between work bouts, gives HIIT its name but has markedly nonlinear effects on average power or pace during HIIT that I will soon discuss.

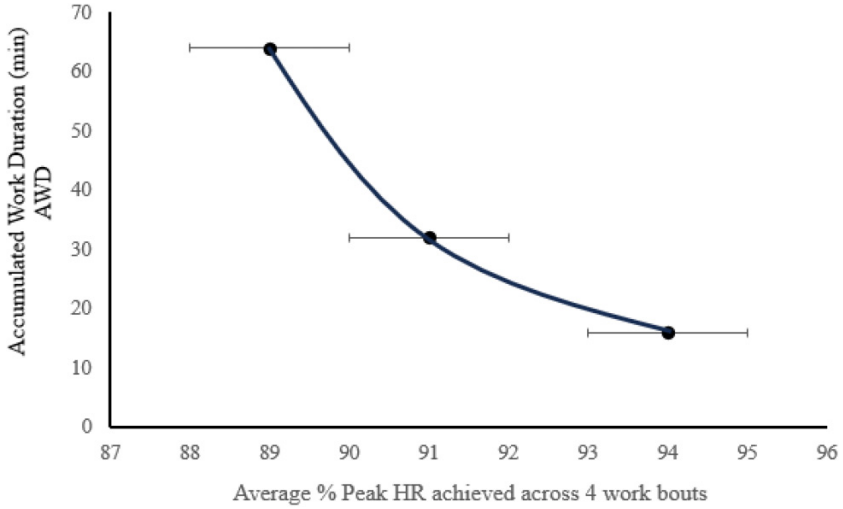
A HIIT training prescription involves manipulating these interactive variables. Already >50 years ago, Per O. Åstrand recognized the interdependence of average work intensity and AWD, and succinctly introduced the search for an "optimal" intensity-duration interaction during high-intensity exercise, writing:

> "*It is an important but unsolved question which type of training is most effective: to maintain a level representing 90% of the maximal oxygen uptake for 40 min, or to tax 100% of the oxygen uptake capacity for 16 min.*" (Åstrand and Rodahl 1970).

When athletes are motivated to make the prescribed HIIT session a hard to near maximal effort, it can be compared to solving a simple algebraic expression with several "knowns" (i.e., prescribed work bout duration, recovery bout duration, and total work duration), and one "unknown". The remaining dependent variable in the HIIT equation that athletes "solve for" is their average power or pace for the prescribed work bouts (Seiler and Sjursen 2004). This physiological algebra also applies to the highly stochastically paced races that are increasingly typical of many endurance disciplines (now often performed on viewer friendly courses with lots of tight turns and short climbs and descents). When racing, it is average velocity, not average power that must be solved for both tactically and physiologically. This results in highly stochastic power/pace distribution in sports like cycling, the cycling portion of Olympic distance triathlon, and cross-country skiing mass-start events.

Given the interdependent nature of the primary HIIT variables, coaches must arbitrarily "start somewhere" when developing the prescription. After years of studying well-trained to elite endurance athletes, I prefer to anchor the HIIT prescription with the previously defined AWD. For example, four work bouts of 4 min duration separated by 2 min, free-intensity recovery periods give an AWD of 16 min. Extending these four work bouts to 16 min duration for each bout gives 64 min AWD. The AWD has a powerful impact on the "pacing" of a HIIT session and therefore strongly constrains the possible range of intensity of the repeated hard efforts within a HIIT prescription. The AWD has a strong "tuning" effect that helps guide the athlete into the desired intensity zone (often upper zone 3, zone 4, or zone 5 in a 5-zone intensity model). Among 63 well-trained cyclists completing each of 3 HIIT sessions up to 8 times in 12 weeks (4 × 4 min, 4 × 8 min, and 4 × 16 min), this 3-fold increase in AWD had only

Fig. 1. Non linear impact of a 3-fold range in HIIT accumulated work duration (AWD) on average % of HR max reached during work bouts. From 63 well-trained subjects performing up to 8 training sessions of each prescription: 4 × 4 min, 4 × 8 min, and 4 × 16 min. Data redrawn from Seiler and Sylta (2017).



a modest effect on HR responses (see Fig. 1), but a large impact on average power output (24% lower), and blood lactate concentration (~5 vs. ~13 mmol·L^{-1}).

Perceptually, only 8% of nearly 500 completed 4 × 16 min sessions resulted in peak RPE of 19–20, versus 61% of 4 × 4min sessions. Thus, "*maximal session effort*" across an entire interval training session is not synonymous with or equivalent to maximal acute perceived *exertion* (RPE) across a range of AWD and intensity combinations typical for traditional HIIT prescription (Sylta et al. 2016; Seiler and Sylta 2017). For example, in response to the same "maximal session effort" prescription, 4 × 16 min work bouts, with 3 min free-range recoveries, elicited an RPE of 13–14 at the end of the first bout, climbing to 16–17 at the end of the last bout, while the 4 × 4 min prescription elicited an RPE of 15–16 at the end of the first bout, climbing to 18–19 by the end of the fourth bout. The 4 × 16 min prescription can be expected to elicit a power output approximating MLSS or LT2. So, strictly speaking, is 4 × 16 min a prescription for "threshold training", or HIIT? I would argue that the answer is a qualified "yes" to both categories, based on power output, heart rate, and RPE responses. Intensity and duration must be integrated to fully capture the dynamic impact of a session prescription. A threshold session prescribed near LT2 drifts upward in physiological response and perception of exertion over time and the stress responses from extensive threshold sessions and intensive HIIT sessions appear to coalesce (Seiler et al. 2007). Using AWD, the basic prescription can be contracted (e.g., 3 × 8 min instead of 4 × 8 min) or expanded (e.g., 5 × 8 min instead of 4 × 8 min) to facilitate a manageable progression or consolidate established capacity without changing prescribed power/pace.

Section 2: Perceptual and physiological responses to HIIT

HIIT training sessions are like a magnifying glass for peering into the remarkable interactions of brain and body during exercise. Those interactions are present at all exercise intensities and durations, but the mind and body "conversation" (famously summarized as "shut up legs" by former professional cyclist Jens Vogt) becomes increasingly heated during HIIT. In the next section, I will delve into the dynamics of that psychophysiological process during a HIIT session, with an eye towards informing training monitoring.

Quantifying *exertion*, *effort*, and *mobilization* during HIIT sessions

The brain's perception of acute *exertion*, as famously translated to psychometric form (RPE) by the late Swedish psychologist Gunnar Borg (1927–2020), seems to be strongly tied to relative exercise intensity. In contrast, *effort* behaves as the integral of "tolerable exertion magnitude × duration of that level of exertion". Different reciprocal exertion and duration combinations are dictated by the prescription (Abiss et al. 2015; Seiler and Sylta 2017).

There are two duration variables in the HIIT prescription, (1) the duration of each work bout (e.g., 8 min in a 4 × 8 min HIIT prescription) and (2) the overall AWD (e.g., 32 min in the same 4 × 8 min HIIT prescription). Of these, the AWD has a greater constraining effect on acute physiological and perceptual responses when HIIT sessions are prescribed as "hard sessions" or "maximal session efforts". For example, in Fig. 2 we see minimal impact on duration above different fractions of VO_2 peak, as a function of how the AWD was achieved (3 × 8 min vs. 6 × 4 min; Fennel and Hopker 2021).

We have also observed very similar physiological and perceptual responses for AWD equivalent prescriptions of 12 bouts × 2 min, 6 × 4 min, and 4 × 6 min even when work: recovery ratio was 1:1 for each prescription (Seiler and Sjursen 2004). It is worth noting that repeated blocks of "micro-intervals", such as 3 × 10 × 40 s:20 s or 3 × 13 × 30 s:15 s induce "central" HR and VO_2 responses that are essentially the same as those induced by continuous work bouts of similar total duration. Table 1 presents unpublished data from

Fig. 2. Impact of work bout duration on achieved intensity when accumulated work duration (AWD) is constant. The same 23 subjects completed 3 sessions for each prescription (69 sessions for each 24 min AWD condition) with different recovery work intensities, prescribed as maximal session effort. Recovery duration was 2 min for the 6 × 4 min prescription and 4 min for the 3 × 8 min prescription. Figure redrawn from Fennel and Hopker (2021).

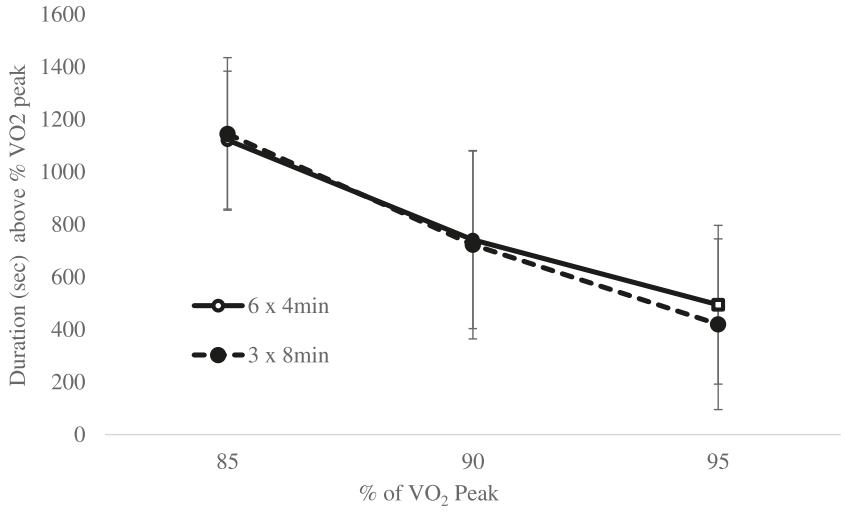


Table 1. Physiological responses to performed as continuous bouts or "mico-interval" blocks with same accumulated duration of work bouts (AWD).

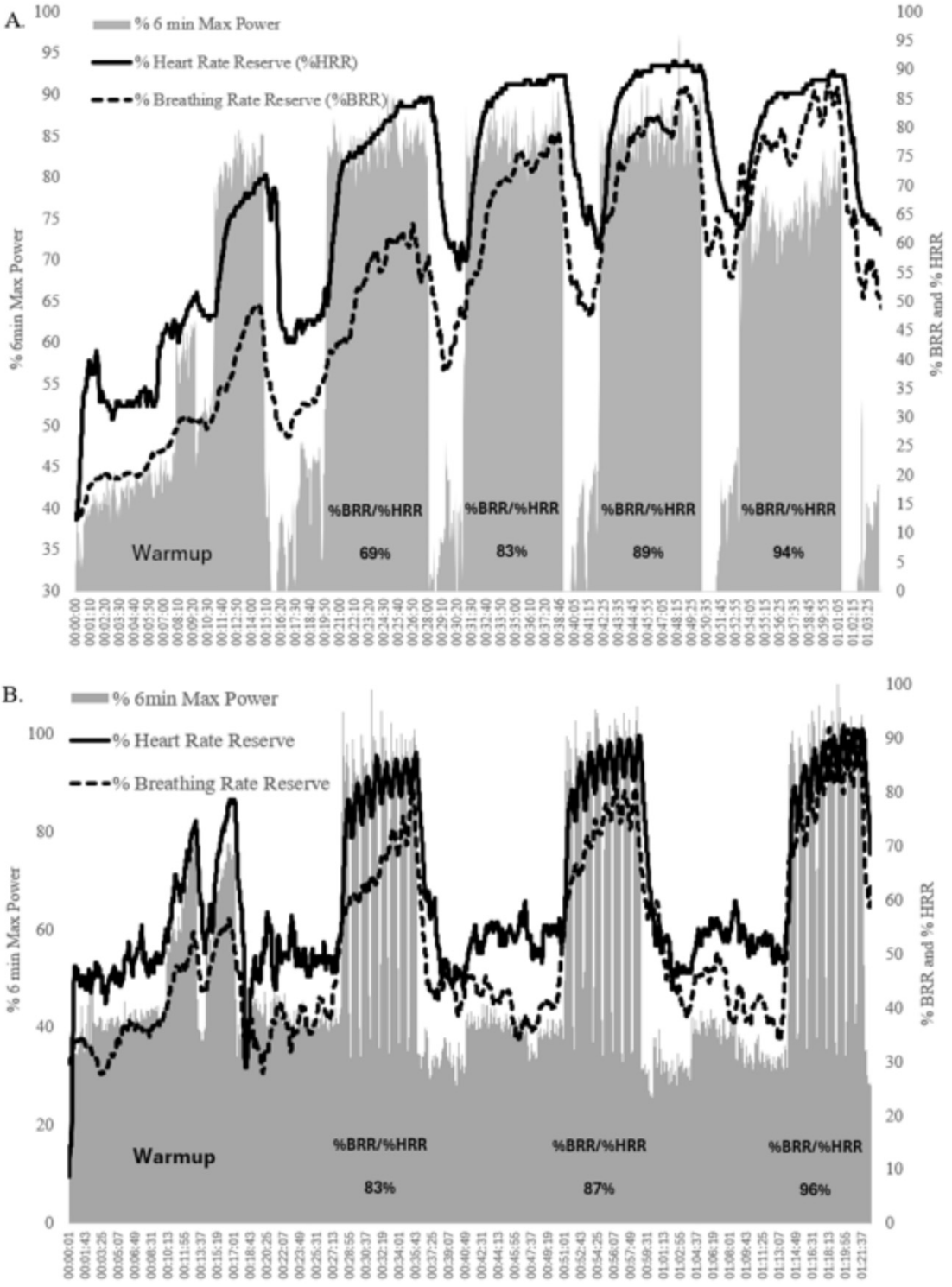
	4 × 8 min (n = 8) 32 min AWD	4 × (12 × 40–20 s) (n = 9) 32 min AWD
Power ($W \cdot kg^{-1}$)	3.7 ± 0.5	4.0 ± 0.3
Percent of PPO	70 ± 3	74 ± 3
Percent power at 4 $mmol \cdot L^{-1}$ lactate	104 ± 6	113 ± 7*
Blood lactate ($mmol \cdot L^{-1}$) work bout 4	8.1 ± 1.4	7.2 ± 2.0
Work bout HR_{mean} (%HR_{peak})	86 ± 2	86 ± 3
Work bout HR_{peak} (%HR_{peak})	90 ± 1	90 ± 3
RPE (6–20)	16.8 ± 0.7	16.7 ± 0.3
sRPE 30 min post session (1–10)	8.8 ± 0.9	8.7 ± 0.8

Note: Values for each condition are means from 12 HIIT sessions performed by each group during a training intervention study. Except for blood lactate concentration and sRPE, values are means of all 4 work bouts/blocks. PPO = peak power output obtained during preliminary testing. RPE = Rating of Perceived Exertion (Borg). sRPE = overall session Rating of Perceived Exertion (Foster). * = <0.05 versus 4 × 8 min condition.

our lab comparing acute responses in well-trained cyclists to prescriptions of either 4 × 8 min or 4 × (12 × 40:20 s) HIIT sessions with the same 32 min AWD. While power output during the numerous, shorter work bouts is moderately higher, the physiological and perceptual responses are virtually identical to a prescription with the same AWD and the same duration of work between longer rest periods.

While heart rate responses tend to approach a *quasi* steady-state toward the end of HIIT sessions, we have recently observed that ventilation responses present a more dynamic picture that better mirrors the steadily increasing perception of effort during hard HIIT sessions. Figure 3 panels A and B present HIIT sessions with the same 8 min work periods (either ~constant power, or as 40:20 s repeats) and similar AWD performed by the author (panel A, age 58, 6 min maximal power (MMP) ~375 W,) and a young World Tour cyclist (panel B, age 22, 6 MMP ~545 W, Panel B). These two figures are instructive because despite massive differences in age, talent, training volume, and physiological capacity, they both reveal what we believe are consistent and reproducible differences in the "rate of decoupling" of the central systemic variables heart rate (HR) and breathing rate (BR) during high-intensity exercise. Valid and practical quantification of ventilation variables outside the laboratory is new and best achieved with wearable technologies that directly and accurately quantify and filter chest wall movements (Massaroni et al. 2021). We are used to expressing heart rate as a percentage of individual maximal heart rate. Like heart rate, breathing frequency also shows repeatable, individual maximal values that are movement modality specific. For comparison purposes, it is convenient to convert both HR and BR to percentages (%) of their respective individually determined *functional reserves*. We can employ the simple Karvonen approach, where heart rate reserve = fractional utilization of maximal heart rate—resting heart rate (%HRR) and breathing rate reserve = fractional utilization of maximal breathing rate—resting breathing rate

Fig. 3. (A and B) Examples of power output versus heart rate and breathing rate progression during two HIIT sessions. (A) Evolution of heart rate (%Heart Rate Reserve) and breathing rate (% of Breathing Rate Reserve) responses during 4 × 8 min HIIT session performed by the author. The last 8 min bout was performed at a lower power due to fatigue. (B) Evolution of cardiac and breathing rate responses (also presented as %HRR and %BRR) in a World Tour cyclist (6 min Maximal Power = 540 W) during a 3 × 8 min × 40/20 s HIIT session.



(%BRR). The %HRR and %BRR both drift upward (decouple) relative to external work rate during prescribed HIIT training sessions. However, the rate, or slope of decoupling can be very different for heart rate and breathing rate, suggesting that they are regulated by different aspects of increasing central demand induced by peripheral fatigue processes. The

ratio %BRR/%HRR seems to have great potential as an objective, real-time indicator of the physiological *mobilization* demanded of the athlete to maintain the intended external output at any given moment during a threshold or HIIT session.

Decoupling of internal and external load during HIIT sessions

HIIT sessions are stressful because the internal cost of achieving the prescribed external load is not static but increases steadily throughout the session. Intermittent recovery periods modestly delay but cannot prevent this decoupling process. Understanding the reasons for and indicators of this escalating "mismatch" between external and internal load during a HIIT session can inform training monitoring and help coaches individualize HIIT prescription to ensure that desired training effects are achieved without excessive stress and delayed recovery.

Executing the HIIT prescription will stress potential perceptual/mobilizing, cardiopulmonary, and skeletal muscle constraints on aerobic performance. As discussed above, cardiac and ventilatory responses are not stable during a HIIT session. Why are they increasing? Independent of potential stroke volume decline due to dehydration and plasma volume loss, both HR and breathing frequency drift upward during HIIT sessions due to their complex regulation and tethering to changing oxygen delivery demand (heart), central command (BR and HR), and CO_2 removal demand (ventilation). Importantly, while HR can be dissociated from RPE, breathing rate regulation is tightly coupled to central command and perceived exertion, as well as CO_2 removal demand via peripheral feedback (Nicolo et al. 2017, Nicolo and Sacchetti 2023). From the work of Nicolo and colleagues, and our own recent field observations of regularly trained to elite athletes using wearable technology, breathing frequency can be uniquely described as both a physiological and a perceptual monitoring variable. HR and BR together are training session "vital signs" that combine to quantify both central and peripheral aspects of the increasing systemic mobilization required across the HIIT session to compensate for contractile fatigue within the interweaved mosaic of motor units in the active muscles.

Importantly, the upward drift of cardiac and ventilatory function from external power/pace exemplified in Fig. 3 seems to be part of a brain-regulated compensatory response to dynamically evolving peripheral fatigue processes at the skeletal muscle motor unit level (see for example Holstrup and Bangsbo 2017), not myocardial or respiratory muscle *fatigue*. For example, Jing et al. (2003) and de Maree et al. (2014) have measured the progressive increase in the magnitude of central command during fatiguing exercise protocols. Importantly, they reveal that increases in the magnitude of central command (the activity of motor and premotor brain areas, assessed via fMRI) temporally coincide with increased EMG activation during fatiguing contractions. However, the magnitude of increase in central command may exceed the relative increase in EMG activation.

Given the severe demands HIIT sessions impose on cardiac and lung performance, it is a question dating back to rowers racing on the Thames 150 years ago whether their performance could be temporarily (or even permanently) damaged by extreme exertion (Hammet 1918; Whorton 1982). While the question of permanent damage has been convincingly dispelled, acute cardiac and respiratory muscle fatigue remains a topic of investigation.

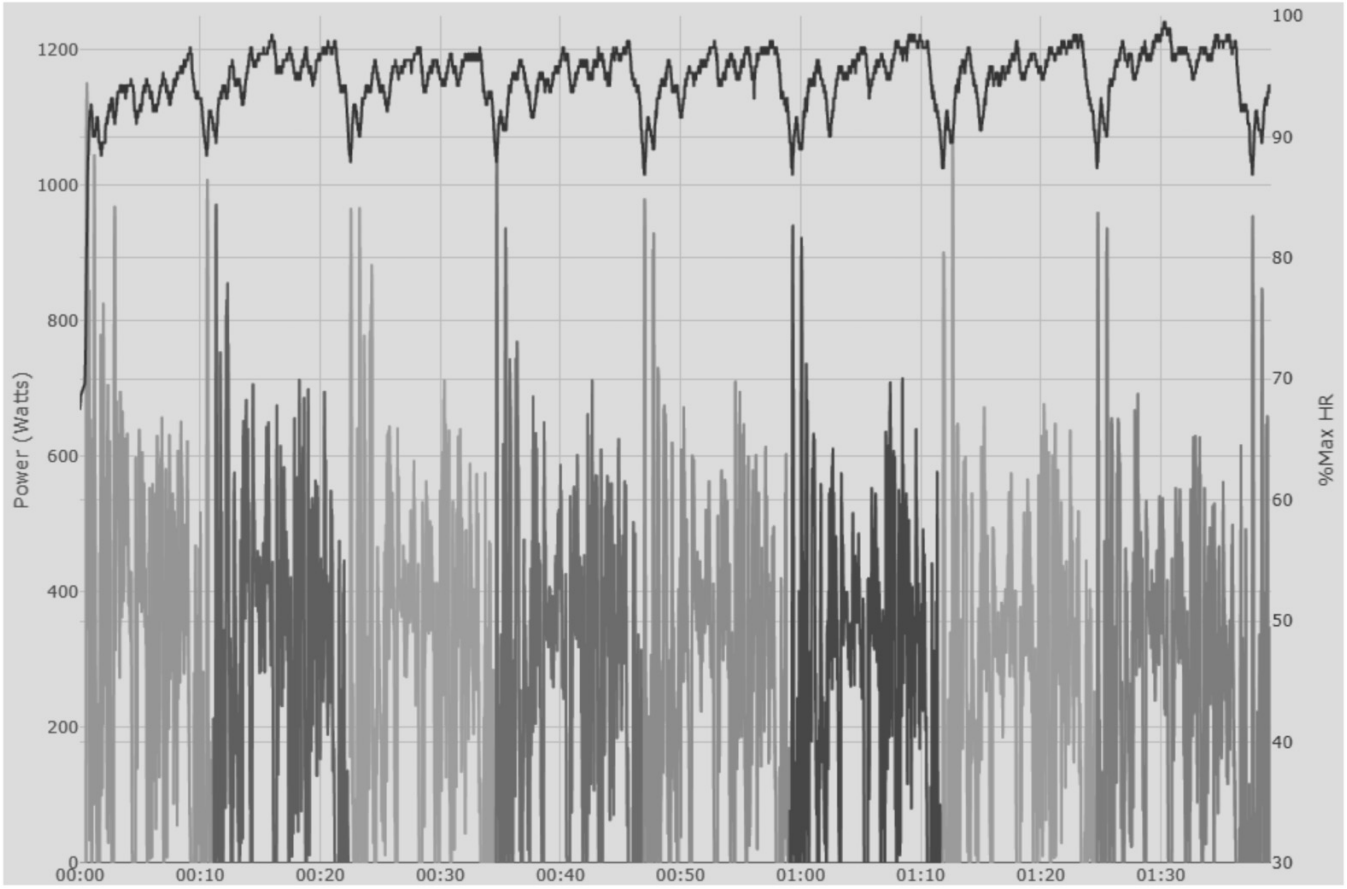
If the myocardium fatigues and cardiac contractile performance declines during HIIT or competition, it is extremely difficult to separate intrinsic myocardial fatigue from hemodynamic changes (i.e., blood flow redistribution and/or plasma volume decline) which alter preload and afterload in the closed loop hemodynamic circuit. The potential mechanisms postulated for acute cardiac contractile/pump dysfunction include altered loading conditions, desensitization of beta-adrenoreceptors, oxidative stress, and pulmonary congestion (i.e., Sengupta et al. 2018). To specifically quantify potential fatigue of the myocardium from endurance exercise, we used an isolated heart model in untrained but run-habituated rats running for ~75 min to exhaustion on a treadmill (unable to avoid a shock grid). Isolated myocardial performance was unchanged compared to control animals (Seward et al. 1995). A systematic review of 23 studies showed that when transient cardiac fatigue was detected, it was primarily associated with either untrained subjects or ultra-distances (Middleton et al. 2006). Similarly, ventilatory fatigue in the untrained to moderately trained also seems to not be a limiting factor for HIIT performance (e.g., Anholm et al. 1989). Even at maximal exercise, ventilation only requires 8%–10% of maximal oxygen delivery in the untrained. However, in the highly trained, near maximal ventilation becomes relatively more costly (~16% of VO_2max), such that their extreme ventilatory demands may negatively impact skeletal muscle performance through competition for cardiac output, independent of a decline in diaphragmatic and/or intercostal muscle contractile performance (see Romer and Polkey 2008 for review).

Understanding the recovery periods that put the *intervals* in interval training

HIIT recovery periods typically last from 15 s to as long as 5 min in duration. These recovery periods facilitate accumulation of greater work time at high percentages of maximal oxygen consumption by partially reducing but not preventing the rate of rise in "internal cost/external work" within the working muscles. Brief, incomplete recovery periods thereby slow the escalation of physiological processes in and around the working muscles that would force a more rapid reduction in pace or power if performed continuously. This is true when executing well-defined, proactive, HIIT prescriptions, but it is also true for highly stochastic and "reactive" real-world races. An extreme example of decoupling of central and peripheral intensity distribution is presented in Fig. 5, from a national/international class mountain bike athlete, showing his power and heart rate data during a 98 min national championship race contested over 8 laps of a highly undulating circuit (Fig. 4).

The athlete averaged 95% of HRmax and 93% of HRR for the 98 min race and heart rate varied relatively little (Fig. 5A)

Fig. 4. Power and heart rate data from a national elite level mountain bike race. Data provided by a World Cup level mountain bike cyclist from his national championship race. Maximal and resting heart rate were provided by the athlete for calibration purposes.



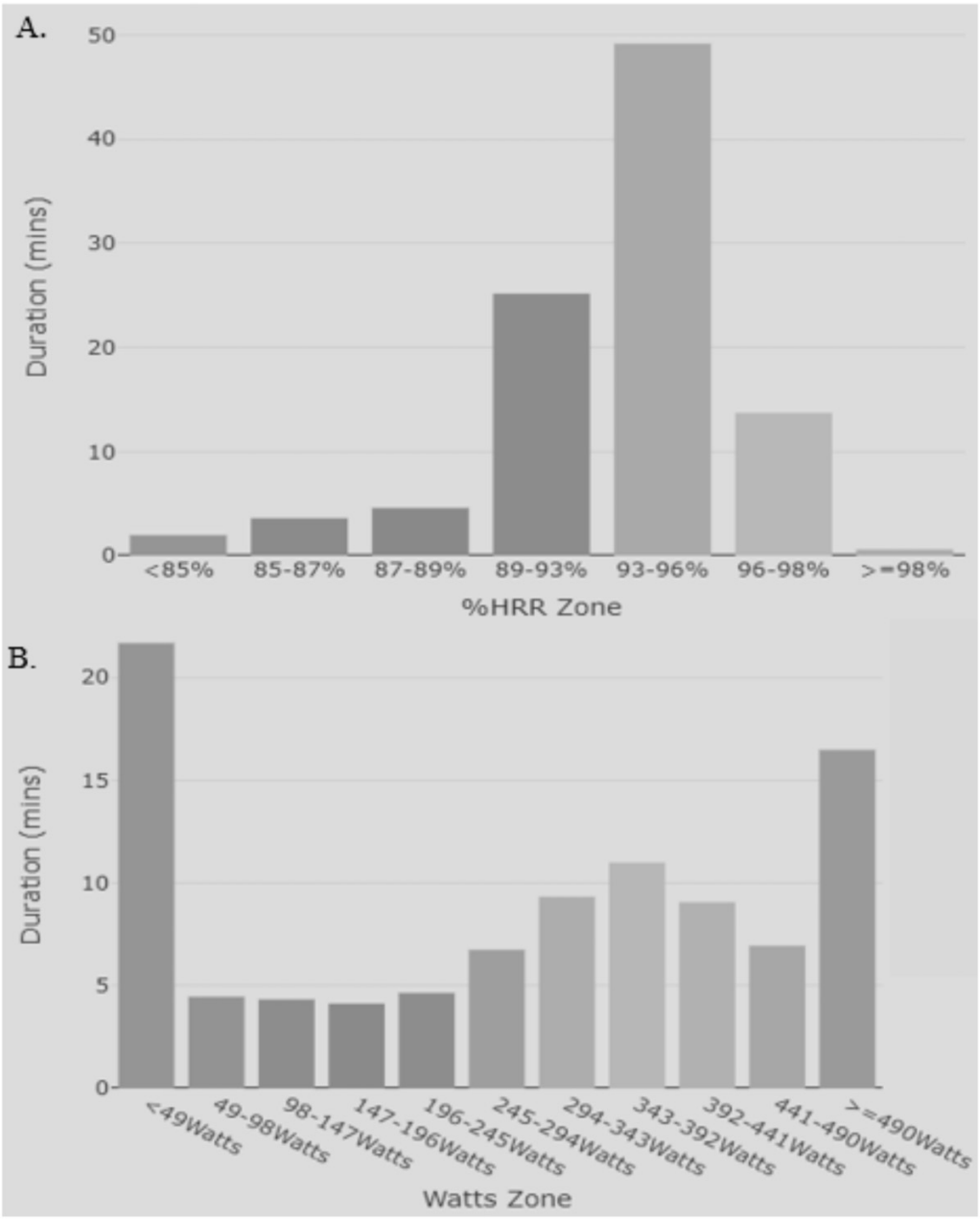
compared to power distribution (Fig. 5B), which varied in a bi-modal manner over a 10-fold range as a function of the loop course topography. Twenty minutes of the 98 min race were spent below 10% and 22 min above 90% of the athlete's "fresh" maximal power output for 6 min (6 MMP). In contrast, heart rate was a "smoothed" function of the stochastic power output and varied only modestly across the race, with ~50 min spent in the narrow heart rate band of 93%–96% HRR (Fig. 6A). The athlete's average power gradually deteriorated across the 8 laps of the race. We can speculate that while HR remained quasi stable over most of the race, breathing frequency gradually increased and was negatively correlated with the power decline.

Thus, the highly dynamic metabolic energy system interactions that are generated in response to a HIIT prescription, or that emerge when responding to the features of the course and rival tactics being negotiated in races, allow the mobilization and accumulation of more minutes of work duration at a high fraction of central capacity before reaching a limiting level of contractile inhibition and disfunction within the increasingly active musculature.

The impact of recovery duration on power output/pace maintenance is highly duration dependent in the 5–60 s recovery duration range, a time span consistent with a somewhat individually variable ~30–60 s half-time for ATP/CP recovery kinetics (Harris et al. 1976; Balsom et al. 1992; Gaitanos et al. 1993; Bogdanis et al. 1995). Importantly, physiological, and perceptual responses to intermittent exercise with very short (s) absolute work and recovery durations are more dependent on *absolute* work and recovery durations than relative work: recovery ratios (Price and Moss 2007).

In contrast, during traditional HIIT sessions with ~2–10 min work bouts, a recovery duration of 2–3 min seems to be an almost universally reasonable recovery prescription because prescribing a minute or two recovery time more, or less, in this range has surprisingly little impact on average work bout performance (Seiler and Hetlelid 2005). In response to the same 6 × 4 min "maximal average work bout speed" self-paced treadmill HIIT prescription, we found that increasing recovery periods from 1 to 2 min resulted in a small but statistically significant increase in self-selected (and blinded) average running velocity from 83% to 85% of the lowest velocity eliciting VO_2max during a preliminary progressive treadmill test to exhaustion (vVO_2max). However, a further increase to 4 min recovery had no additional effect on average running velocity (84% vVO_2max). Indeed, across a range of 1–4 min recovery time, blood lactate concentration, RPE, and HR responses were all very similar. Further, when sub-

Fig. 5. (A and B) Frequency distribution for heart rate and power output during the mountain bike race presented in Fig. 4. (A) Distribution of % heart rate reserve based on resting and HRmax values provided by the athlete. (B) Power distribution, with 490 W estimated as maximal power for 6 min (6 min maximal power) from training and testing files.

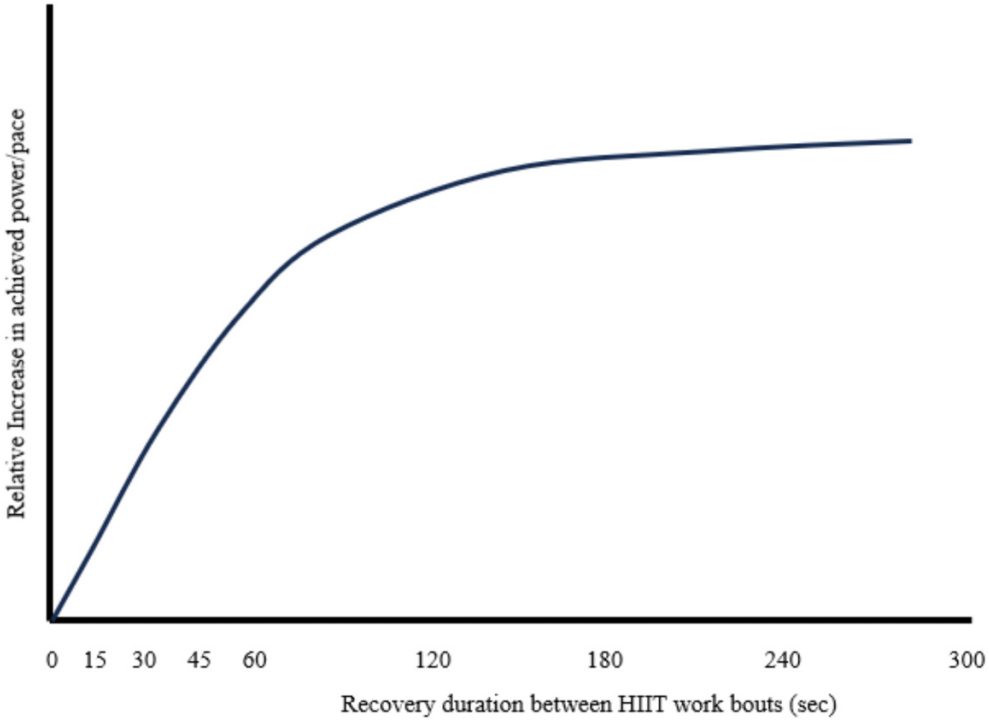


jects were challenged to repeat the completed HIIT session with the best previously achieved average treadmill velocity but were blinded to recovery duration and told to self-select the *minimum* time required to maintain the intended treadmill velocity, they chose a recovery duration of 118 ± 23 s. This ~2 min self-selected recovery time did not change significantly across the 6 × 4 min HIIT session. Presumably the highly nonlinear relationship between recovery duration and achieved power/pace during a traditional HIIT session (exemplified in Fig. 6) is best explained by the fact that from ~1 to 5 min, these recovery durations all achieve near complete high energy phosphate restitution but have little impact on blood lactate and pH concentration (Hargreaves et al. 1998), given that the half-time for blood lactate elimination can exceed 20 min (e.g., Sharp et al. 1986; Rieu et al. 1988; Juel et al. 2004).

Section 3: Cellular and systemic adaptations to HIIT

In Section 1, I presented my views on HIIT programming in the context of the overall endurance training process. In Section 2, I explored the dynamic physiological and perceptual responses observed during HIIT sessions, the decoupling of internal and external load that occurs, and how quantify-

Fig. 6. Non linear impact of recovery interval duration during high-intensity interval training (HIIT) on achieved power/pace during HIIT sessions when prescribed as "hard to maximal session efforts".



ing this decoupling can inform training monitoring. In this final section, I will defend my views on HIIT programming by delving into the adapting cells and the adaption driving molecular signals that are turned on by endurance training in general, and HIIT specifically.

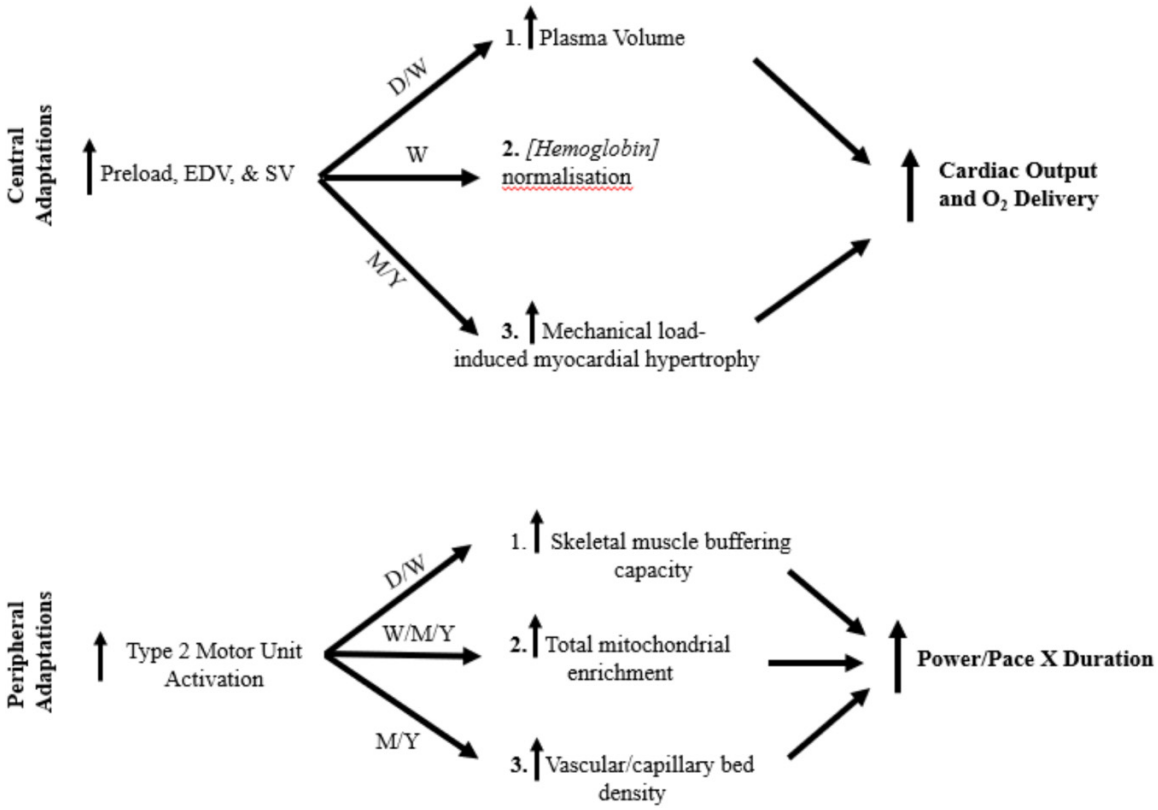
Overlapping and additive adaptive effects across training intensity zones

HIIT prescriptions offer lots of room for creativity and variation. This variation can be important for long term athlete motivation and development. However, I see little evidence that any one HIIT prescription is "best" over time. There are many ways of getting to the same combination of motor unit recruitment and overall physiological mobilization with different combinations of intensity and accumulated work duration. In fact, case studies of champion endurance athletes suggest simplicity in the HIIT sessions they perform (e.g., Keleman et al. 2024; case studies cited in Staff et al. 2023). The physiology is complex, but HIIT training prescriptions can be simple and still effective.

To make progress towards individual optimization of HIIT prescription, scientists and coaches must both successfully bridge two very different time scales (Fig. 7). The first, "acute", time scale has received the most research attention and involves the minutes and hours during and immediately after an individual HIIT session. Exercise in general and HIIT in particular is a powerful stimulus for gene upregulation across multiple cell types. The execution of prescribed training generates a coordinated symphony of molecular signals at the cellular level across the entire oxygen delivery and utilization cascade from myocardium to mitochondria. These signals can rapidly induce upregulation of the synthesis of specific proteins and protein structures resulting in enhanced buffering capacity (Weston et al. 1996), increased enzyme density within existing mitochondria, expansion of the mitochondrial reticulum within muscle fibres (Bishop et al. 2014, 2019), and capillary angiogenesis around active myocytes through paracrine expression of vascular endothelial growth factor (e.g., Olfort et al. 2010). Given the blended fibre-type mosaic of motor units and individual myocytes in the 3D volume of locomotor muscles, there is likely considerable spatial overlap in driving increased capillary density across exercise intensity. Peripherally, compared to regular LIT, HIIT training would be expected to extend mitochondrial and capillary density adaptations deeper into the Type 2 fibre population (See Fig. 7). Mitochondrial and capillary density adaptations appear to develop in a highly coordinated manner (Hoppeler and Kayar 1988). Importantly, the additive impact of HIIT on these different peripheral performance determinants depends critically on training status.

At the central level, regular LIT and HIIT both initially induce plasma volume expansion via increased hepatic albumin and globulin protein production and enhanced colloidal mass in the intravascular volume (e.g., Röcker et al. 1976). A modest 200–400 mL plasma volume (PV) expansion in untrained participants improves stroke volume performance and maximal oxygen consumption (despite temporary haemodilution), supporting that this early PV adaptation to both LIT and HIT is functionally important (Hopper et al. 1988; Coyle et al. 1990). HIIT appears to drive an additional small increase in PV compared to that induced by regular LIT

Fig. 7. Key central and peripheral effects of regular high-intensity interval training when added to substantial volumes of low-intensity training (<LT1). Relative timelines for peaks of these adaptations are estimated as days (D), weeks (W), months (M), or years (Y) based on published longitudinal studies, and anecdotal data shared by coaches and athletes. EDV = end diastolic volume, SV = stroke volume.



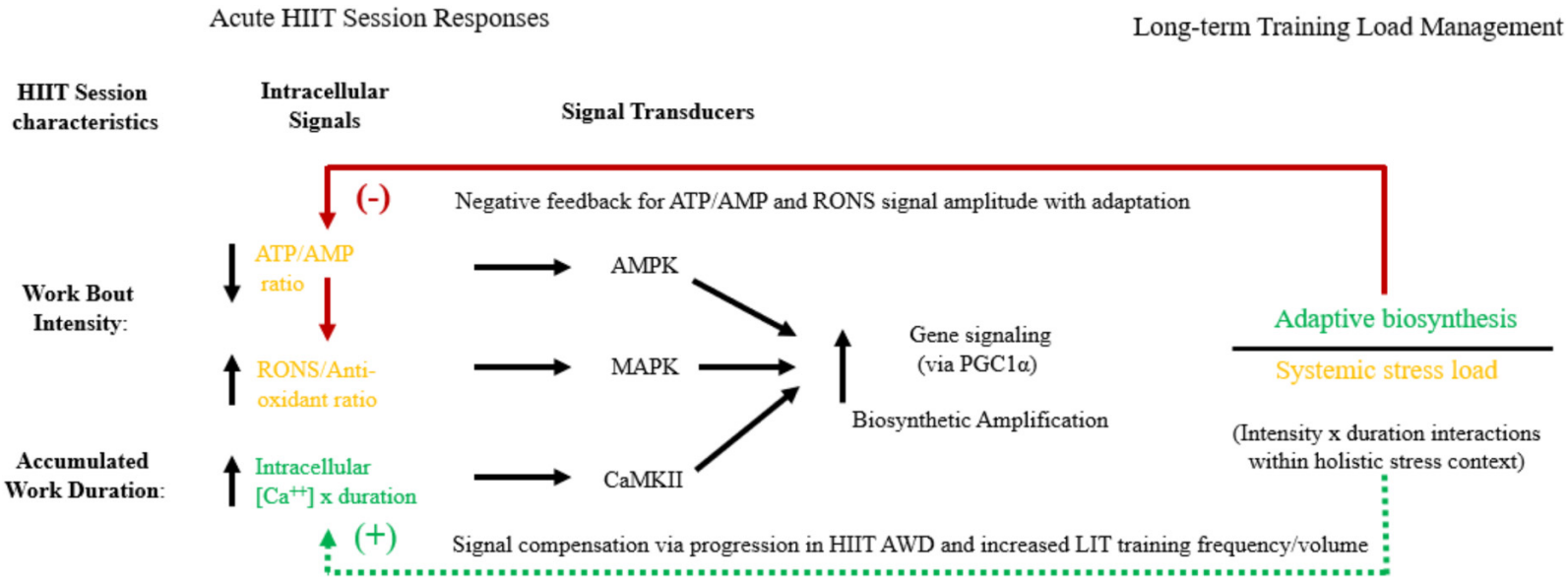
training (Mandic et al. 2022, 2023; Zohal et al. 2023). Chronologically, increased PV (via its impact on end-diastolic volume and cardiomyocyte loading) may be an important prerequisite for the slower development of additional and reversible (Pellicia et al. 2002) myocardial hypertrophy and enhanced stroke volume over months and years of endurance training (e.g., Krip et al. 1997; Arbab-Zadeh et al. 2014; Bonne et al. 2014; Bjerring et al. 2019, 2021; see Fig. 7).

Different cellular signalling pathways towards the same adaptations

The "adaptive signal" amplitude (or amplitude × duration area under the curve) and translational impact on biosynthesis rate(s) of any form of endurance training is highly dynamic. For example, up to 900 different genes are activated when an untrained adult performs an acute bout of endurance exercise but falls precipitously to <10% of that number of exercise perturbation sensitive genes in well-trained subjects (Pillon et al. 2020). The untrained to endurance-trained transition is both dynamic and profound. In this context, the specific impact of a given HIIT stimulus on molecular signalling will also be dynamic and has been shown to change dramatically across relatively few iterations of the same HIIT prescription (e.g., Granata et al. 2018, 2020; McConell et al. 2005). These findings perhaps highlight that no one aspect of maximal functional expression of the "endurance phenotype", such as mitochondrial alterations/proliferation, should be overemphasized given the long timescale of peripheral adaptations. It is also likely that other cellular adaptations that are even more challenging to visualize and quantify are also functionally important (i.e., Hostrup and Bangsbo 2017).

As depicted in Fig. 8, we can now describe at least 3 adaptive signalling pathways through which HIIT can impact protein composition of working muscle over time: (1) intracellular high energy phosphate depletion and large reductions in ATP/AMP ratio during high-intensity exercise (e.g., Winder et al. 2006), (2) elevated production of reactive oxygen and nitrogen species (RONS) commensurate with massive relative fold changes in oxidative flux within a muscle fiber (e.g., Mason et al. 2020), and (3) elevated intracellular calcium concentration associated with the excitation–contraction coupling process (e.g., Rose et al. 2007; Tavi and Westerblad 2011). These pathways all have well-demonstrated signalling roles, mediated through specific kinases, and aggregated by PGC1α (Hoppeler 2016). Importantly, the pathways triggered by high-energy phosphate depletion and by RONS both show rapidly evolving feedback inhibition of signal amplitude as signal mediated adaptations occur (e.g., Granata et al. 2018, 2020; McConell et al. 2005). That is, adaptive feedback inhibition results in diminishing adaptive return from these path-

Fig. 8. Acute intracellular signaling pathways and long-term adaptation to high-intensity interval training (HIIT). Potential redundancies and mechanisms of diminishing adaptive signaling effect are presented in the figure. Sources of variation when translating from acute HIIT responses to long-term adaptation are listed below the figure. RONS = reactive oxygen and nitrogen species. AMPK = AMP-activated protein kinase. MAPK = mitogen-activated protein kinase. CAMKII = calcium/calmodulin-dependent protein kinase II.



Sources of variability in the **acute** HIIT response

- Signaling redundancy
- Intensity/duration interactions
- Fiber type composition variation
- Training status
- Antioxidant protection
- Energy availability
- Environmental factors

Long-term sources of HIIT adaptive impact

- Systemic Recovery kinetics variation
- Frequency-Intensity-Duration interactions
- Diminishing return effects
- Overall training stress management
- Interactions with other stressors
- Environmental factors (heat, altitude, etc.)
- Epigenetic modification effects
- Placebo/Belief effects

ways with repeated HIIT bouts over time. There is also almost certainly crosstalk among these signals, particularly between the RONS and energy depletion pathways. For example, several studies have shown that large doses of Vitamin C and E in combination blunt some but not all the skeletal muscle adaptations to endurance training (Ristow et al. 2009; Paulsen et al. 2014; Margaritelis et al. 2018). In contrast, we can speculate that the Ca^{++} activated myokinases (several variants) remain responsive across longer training time frames due to (1) greater potential for modulation via exercise duration × intensity interaction and (2) essentially no feedback inhibition of the primary signal, which is an intensity × duration dependent increase in intracellular [Ca^{++}], within and across motor units.

Balancing signal and stress for long-term development

To further complicate predictions about the specific impact of HIIT in a sustainable, long-term endurance training process, there is a large systemic "stress response cost" to using high-intensity exercise to achieve desired cellular stimuli in muscle fibers, heart tissue, vascular matrices, and inducing "soft protein adaptations" such as increased blood buffering capacity. A holistic manifestation of this systemic cost is longer perceived recovery times and reduced readiness to train after too frequent or too intensive HIIT sessions (e.g., Nuuttila et al. 2022). However, here the research seems to be behind the accumulated wisdom of numerous high performance endurance environments regarding the fine-tuning of HIIT session intensity and AWD characteristics to ensure reasonable recovery from day to day across extended training periods (Casado et al. 2023; Sandbakk et al. 2023). As Fig. 8 depicts, the "optimization" of HIIT cannot be seen in isolation. Accumulated signalling from all exercise stimuli, including HIIT, must be balanced to ensure sustainable overall cellular *signal* versus systemic *stress* management across days, weeks, and months of training.

Predicting the (1) "magnitude" of adaptive signal, (2) resulting downstream signal transduction to amplified protein synthesis and ultimately, (3) functional improvement resulting from any specific HIIT stimuli is profoundly complex due to the inherent nonlinear, redundant, and highly overlapping impact of different acute and chronic states at the local and systemic level (see Fig. 8).

From generalizable HIIT practice toward individual optimization

While searching for "optimal" isolated HIIT sessions seems overly simplistic, we can potentially combine insights from intracellular signalling, systemic physiology, and effective training monitoring to better individually optimize the overall endurance training process, including the integration of HIIT across the long-term training cycle. A small dose of HIIT regularly performed can markedly improve physical capacity in both untrained and trained persons (Gibala et al. 2012). The adaptive impact of HIIT can evolve differently as a function of intensity and AWD periodization (Sylta et al. 2017) and just adding more HIIT is not better (Rosenblat et al. 2021). While HIIT is often termed "VO_2 max training", bodyweight adjusted maximal oxygen consumption typically plateaus very early in endurance athlete development (e.g., Ingjer 1992), while peripheral adaptations both fluctuate more within a season (e.g., Lucia et al. 2000) and show a much longer time to peak adaptation (e.g., Jones 2006).

Conclusions: tying HIIT programming, responses, and adaptations together

Human psychobiology is complex and defies linear planning/periodization paradigms (e.g., Kiely 2018) or identification of any single "best" HIIT prescription. Currently, I would summarize our pursuit of effective HIIT optimization as follows:

1. It is important to see HIIT in the context of the many hours of LIT that need to be performed for optimal health and adaptation over time. LIT and HIT are best seen as synergistic in adaptive effect over months and years of regular endurance training.
2. The HIIT prescription includes intensity and AWD as key levers for tuning the high-intensity training stimuli from session to session. These should be used in a coordinated way that balances the adaptive signalling function of HIIT against the greatly magnified systemic stress responses resulting from these sessions.
3. HIIT prescription variables serve to partially decouple central and peripheral responses. HIIT sessions are highly dynamic, with continuously evolving peripheral fatigue that drives continually increasing internal stress responses associated with a given external load. Preliminary evidence suggests that combining heart rate and breathing rate quantification can enhance real time feedback on the mobilization demands of a training session and guide prescription.
4. The translation path from HIIT session to induced molecular signal to objective performance enhancement for any form of endurance training stimuli is multiply redundant, highly complex, and decidedly nonlinear. Experimental details of this translation pathway remain unknown and high-performance environments have developed practical, if not mechanistic knowledge regarding this process.
5. Redundancy in intracellular signalling combined with dynamically evolving peripheral fatigue and central mobilization processes contribute to large overlap in the adaptive impact of diverse HIIT training prescriptions.
6. The complexity of our psychophysiology must be matched with simple but responsive monitoring tools that triangulate towards sustainable integration of HIIT without overcomplicating the daily decision-making process. Physiology is complex, but training prescriptions do not need to be.
7. Long-term endurance training is an optimization problem, not a maximization problem. Optimization means that more is not necessarily better and effective HIIT prescription is best achieved by balancing both acute and long-term goals.

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Data availability

Data from relevant articles published by the author, unpublished study data, and training/racing case datafiles summarized as figures in this viewpoint article are available from the author upon reasonable request.

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