The moderating role of recovery durations in high intensity interval training protocols

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Title page

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Abstract:

Purpose: Over recent years, multiple studies have tried to optimize the exercise intensity and duration of work intervals in high intensity interval training (HIIT) protocols. Whilst an optimum work interval is of major importance to facilitate training adaptations, an optimum HIIT protocol can only be achieved with an adequate recovery interval separating work bouts. Surprisingly little research has focussed on the acute responses and long term impact of manipulating recovery intervals in HIIT sessions. This invited commentary therefore aims to review and discuss the current literature and increase the understanding of the moderating role of recovery durations in HIIT protocols.

Conclusion: The acute responses to manipulations in recovery durations in repeated sprint training (RST), sprint interval training (SIT) and aerobic interval training (AIT) protocols have recently begun to receive scientific interest. However, limited studies have manipulated only the recovery duration in RST, SIT or AIT protocols to analyze the role of recovery durations on long term training adaptations. In RST and SIT, longer recovery intervals (≥ 80 sec) facilitate higher workloads in subsequent work intervals (compared with short recovery intervals), whilst potentially lowering the aerobic stimulus of the training session. In AIT, the total physiological strain endured per training protocol appears not to be moderated by the recovery intervals, unless the recovery duration is too short. This invited commentary highlights that further empirical evidence on a variety of RST, SIT and AIT protocols and in other exercise modalities than cycling is needed.

KEYWORDS: HIIT, protocol optimization, rest intervals, work: rest ratio

Introduction:

High intensity interval training (HIIT) is regarded a highly effective training modality to improve cardiorespiratory and metabolic functioning, and is common practice in training regimes of many athletes, particularly those involved in endurance events. [1] In HIIT, repeated periods of vigorous exercise (work interval) are interspersed with recovery periods, and a complex interplay between the number of intervals, the exercise intensities and the duration of both the work and recovery intervals determine the workload of a HIIT session. [2,3] Based on the duration and exercise intensities of work intervals, HIIT can be divided into multiple training forms, for which many terms exist. In this invited commentary we will use and discuss the terms repeated sprint training (RST), sprint interval training (SIT) and aerobic interval training (AIT) as the three main subcategories of HIIT, each targeting different physiological, neuromuscular and mechanical adaptations. [1] In recent years, many studies have tried to optimize the work intervals of HIIT protocols. A demanding 'work interval' is needed to facilitate training adaptations, with adaptations determined at a cellular level by heat shock proteins, PCG1a and other components [4], but a successful HIIT protocol can only be achieved when work bouts are separated by an adequate recovery. Surprisingly little research has explored the overall impact of recovery intervals, and a better understanding of optimum exercise intensities and recovery durations in HIIT protocols is therefore timely. This invited commentary will 1) review the current knowledge of the moderating role of recovery duration on high intensity protocols, and 2) form a basis from which coaches and sports scientists can optimise HIIT protocols according to their specific targets. Characteristics of all reviewed studies are summarized in Supplementary material Table S1

Recovery Intervals in HIIT: How are recovery intervals usually determined?

A multitude of approaches are available for the prescription of recovery intervals in HIIT. The most common approach is the use of a fixed work:recovery ratio (i.e., W:R = 2:1, 1:1, 1:8). A fixed W:R ratio separates work intervals by an *a priori* set recovery duration, for instance, when W:R = 1:2, the recovery duration is twice the duration of the work interval. In an attempt to individualize recovery intervals, the return of heart rate (HR) to a set threshold value or to a percentage of maximum heart rate (HRmax) is used. However, the present understandings of the determinants of HR recovery suggest that this practice is not appropriate in the prescription of recovery durations. This was for instance evidenced by Edwards et al., [5] who reported decreases up to ~10-15 sec for each 1000m running effort in a 5*1000m sequence when recovery intervals where based on HR return, compared to a W:R = 1:1 protocol, of which the latter resulted in ~80 sec extra recovery time between repetitions. Lastly, a number of studies have used self-selected (SS) recovery durations in HIIT protocols, in which athletes started subsequent work intervals when they felt 'adequately recovered to exercise at the required intensity'. [5–10] While a considerable amount of variation was evident in SS recovery durations across different HIIT protocols, and SS recovery time is potentially dependent on maturation status [7,10] (see figure 1), the current understanding is that athletes can adequately select recovery durations to achieve the required exercise intensities in subsequent work intervals in both RST and SIT (see figure 1) and AIT (see figure 2). Athletes new to the use of SS recovery intervals will likely choose a 'shorter than optimal' recovery time, as common HIIT protocols typically incorporate 'short' recovery durations (e.g. 1000m work : 200m recovery), which potentially compromises training effects.

>> figure 1 and figure 2 around here <<

Physiological basis of recovery.

The main metabolic processes that take place during recovery from intense exercise bouts are the repletion of phosphocreatine stores (PCr), the removal of hydrogen ions (H+) and restitution of the acid-base balance of the exercising muscles. [1,11,12] These processes proceed at different rates, with PCr having a much faster half-life (~30 sec) and achieving complete restoration (~3 min), [11] compared with blood lactate [BLa] and pH recovery (6 - 10 min). [12] In order to work at the required exercise intensity during subsequent intervals, recovery intervals need to be long enough to accomodate the return to metabolic homeostasis. An imbalance between the demands of the work intervals and the recovery potential of the recovery intervals can lead to premature fatigue, which potentially reduces the number of planned intervals, or lowers the work intensity during subsequent intervals. An example of an inadequate W:R is seen in the study by Laursen et al., [13] who reported that two groups of well trained cyclists completed only 64% of the total prescribed number of work bouts over a 4 week training cycle. Participants were 'pushed to exhaustion' in each session, as inadequate recovery had been prescribed given the intensity of the work interval, resulting in failure to complete the session. While the training intervention still improved time trial performance, peak power output (POpeak) and the maximum oxygen uptake ($\dot{V}O_2$max), [13] a protocol involving a longer recovery interval may have evoked even greater improvements.

The recovery duration during RST & SIT

Repeated all-out (or sometimes labelled 'supramaximal' [4]) sprint training has received a growing research interest, as it replicates the demands of maximal-intensity sprint efforts typically performed in field-based team sports and endurance sports. In practical terms, based on the duration of the sprints and the subsequent recovery duration, sprint training can be divided into either short (3–10 sec; RST) or long (15–30 sec; SIT) sprints.

In RST, a positive effect on performance in subsequent 4 – 8 sec supramaximal sprints in cycling power [14–17] and running speed [18,19] has been reported when longer recovery durations were employed. Longer recovery intervals resulted in a lower average HR and oxygen uptake ($\dot{V}O_2$) over the training session. [14,15,17,20] Further, the fatigue index (percentage decline between POpeak first and last sprint), [BLa] and ratings of perceived exertion (RPE) were lower when sprints were interspersed with longer recovery intervals, [15,19] which was accompanied by a greater muscular re-oxygenation. [20]

In SIT protocols similar beneficial performance outcomes were reported across a multitude of exercise modalities when recovery duration was increased between work intervals. [8,21–23] McEwan et al., [8] compared the acute physiological responses and running performance in 12 × 30 sec sprints, wherein the recovery duration was either fixed (30 sec) or self-selected (SS). SS recovery time increased over the protocol (see figure 1) and averaged 51±15 sec. The longer recovery intervals in SS resulted in a reduced time ≥ 90% HRmax, but facilitated the attainment of significantly higher running speeds. In agreement with these findings, Gosselin et al., [24] reported a decrease in mean and peak $\dot{V}O_2$ and mean HR in a SIT protocol alternating 60 sec work intervals with 60 sec recovery, compared with 30 sec recovery intervals. Less than 30 sec recovery between 'all out' sprints seems to have a detrimental effect on power production in subsequent cycling sprints, whereas the aerobic demand in sprints separated by 120 sec recovery are too low to induce endurance adaptations. [22–24] Kavaliauskas et al., [23] therefore suggested 80 sec recovery intervals between sprints are optimal when targeting both power and endurance adaptations.

The recovery duration during 'aerobic' interval training

HIIT incorporating long work intervals (up to 16 min) is typically described as 'aerobic interval training' (AIT), as work intensities are undeniably high - but ultimately submaximal. It was suggested by Thevenet et al., [25] that the time athletes spend in their 'red zone' per AIT could serve as a good criterion to judge the effectiveness of a protocol. The 'red zone' refers to the intensity domain close to $\dot{V}O_2$max (≥ 90% $\dot{V}O_2$max) in which the oxygen delivery and utilization systems are maximally stressed. [1] Previous research showed that trained runners reach a steady state of around 90 - 95% $\dot{V}O_2$max / HRmax across repeated 4 min work intervals, independent of an increased recovery duration between bouts. [6,9,26,27] Both Smilios et al., [27] and Schoenmakers [9] reported changes in the O_2 and HR kinetics when recovery durations increased (more so, mean response time was faster when intervals started from a lower metabolic rate), resulting in similar time spent ≥ 90% and 95% $\dot{V}O_2$max and HRmax between the different recovery durations, suggesting a comparable physiological load of the AIT protocol. [9,27] Increasing the recovery duration from 1 to 4 min did not significantly affect [BLa] responses following each 4 min work intervals in runners, suggesting a balance between lactate production and lactate buffering capacity. [6,26] In a study where participants were working at a greater intensity, a greater [Bla] was evident when 6 x 2 min cycling intervals were separated by either 1 (AIT1) or 3 min (AIT3) passive recovery intervals. [28] The shorter recovery intervals in AIT1 induced a lower post exercise PCr content compared with AIT3, however, these larger perturbations in muscle metabolites did not result in greater training adaptations in AIT1 compared with AIT3. [28]

Using self-paced AIT protocols, in which work intensities were not predefined but rather determined by the integrative outcome of feedback from external and internal receptors, multiple research groups [5,6,9,26,29] have evaluated running performance across work intervals. In highly trained runners, increasing the recovery duration in a 10*400m set speed sequence (60 vs. 120 vs. 180 sec) resulted in a lower RPE. [29] Trained male [6], and recreational active male and female runners [26] were able to increase their mean running speed in 6 × 4 min intervals when the recovery duration was increased from 1 min to 2 min. A further increase in recovery duration (4 min) did not provide extra performance benefits for the trained runners. [6] Conversely, Laurent et al., [26] reported an additional increase in running speed when extra recovery time was available. Schoenmakers et al., [9] reported the highest mean running speed when 6 × 4 min intervals (ran on a curved non-motorized treadmill) were separated by 3 min, compared to 1 min, 2 min or a SS recovery interval. These results overall indicate that adequate recovery will result in the attainment of the desired work intensity within the limits and requirements of a specific protocol, however, the 'optimum' recovery duration, most likely is highly individual and depending on training status.

Practical Applications

In RST and SIT protocols, longer recovery intervals (≥ 80 sec) facilitate higher work intensities in subsequent sprints and lower the fatigue index, whereas a shorter recovery duration in these protocols increases the overall physiological demands of a training session. [22,23] Long recovery intervals in AIT protocols allow athletes to attain higher workloads (speed or power) in successive work bouts when exercise intensities are not fixed, without compromising the overall physiological stimulus of a training session. [6,9,26] When work intensities are fixed in AIT protocols, the same training sessions is typically completed with a lower RPE when longer recovery intervals are available, again, without compromising in the physiological stimulus. [27–29] Ultimately, depending on the exercise intensities of work intervals, a recovery interval of 3 min is expected to be sufficient to avoid premature fatigue in AIT protocols.

Conclusion

The acute responses to manipulations in recovery durations in RST, SIT and AIT protocols are receiving increasing scientific interest. The manipulation of recovery durations in RST and SIT protocols results in different acute physiological and perceptual responses, and most likely in different training adaptations. The current understanding is that training at higher workloads in RST and SIT protocols elicit greater adaptations in POpeak and $\dot{V}O_2$max, however, this has only been evidenced in cycling protocols. In AIT, the physiological strain endured per training protocol appears not to be moderated by the recovery intervals, unless the recovery interval is too short and causes premature fatigue. When adequate recovery intervals are available in AIT protocols, a further increase in recovery duration is not expected to provide greater physiological and/or performance adaptations when exercise intensities are fixed. However, when work intensities are not predefined, longer recovery durations may facilitate a higher external training load, and may therefore allow for greater training adaptations. Further empirical evidence on a variety of RST, SIT and AIT protocols in exercise modalities other than cycling are needed to fully determine the moderating effects of recovery duration in HIIT sessions.

Acknowlegdements

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Figure captions:

Figure 1: Mean±SD self-selected recovery duration between 12 x 30 sec [8] , or 12 x 30m [7,10] intervals

Figure 2: Mean±SD self-selected recovery duration between 6 x 4 min [6,9] , or 5 x 1000m [5] intervals

Table caption

Table 1: Summary of participant and training characteristics of reviewed studies

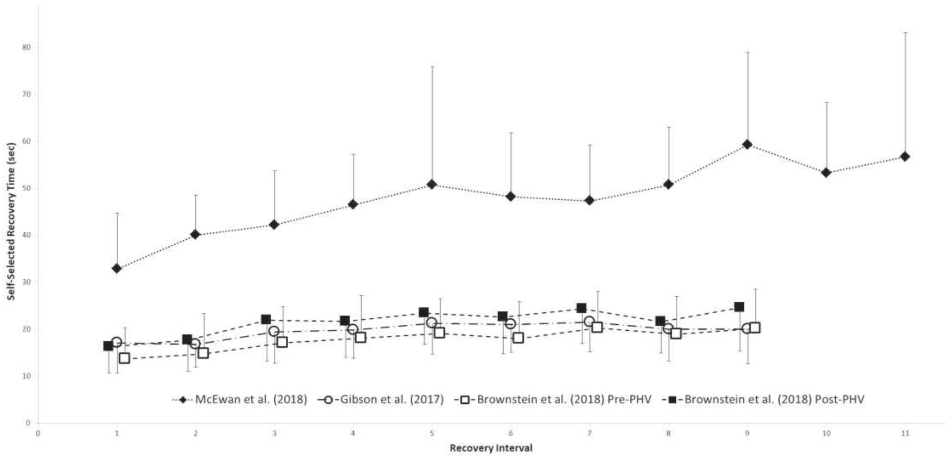

Figure 1: Mean±SD self-selected recovery duration between 12 x 30 sec 8 , or 12 x 30m 7,10 intervals

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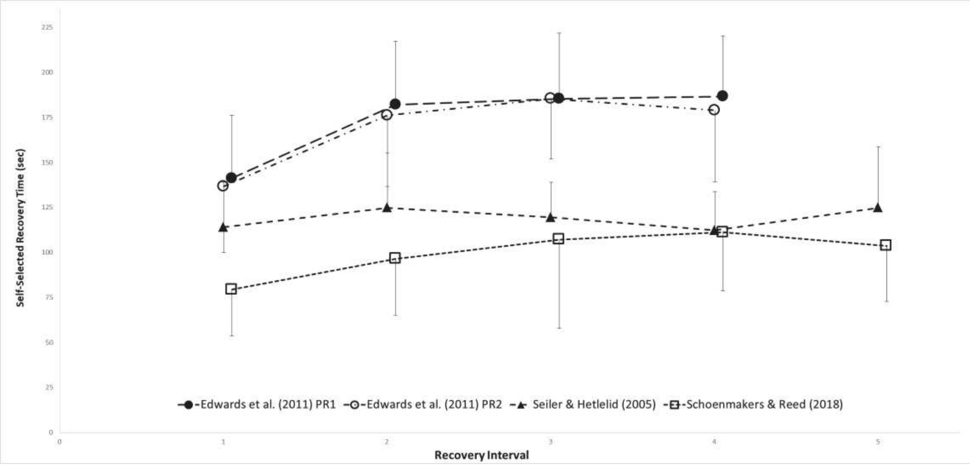

Figure 2: Mean±SD self-selected recovery duration between 6 x 4 min 6,9 , or 5 x 1000m 5 intervals

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Table 1: Summary of participant and training characteristics of reviewed studies

Study	Sample Size, Age	Modality	High Intensity Interval Training Protocol	Recovery Duration	Key Findings
Repeated Sprint Training					
Baker et al. (2007) [15]	n = 8, 26.6 ± 7.8	Cycling	Participants performed 8 × 6 sec sprint on a cycling ergometer against 0.75 $g.kg^{-1}$ FFM or TBM	30 sec, 1MIN	AR: Peak power output was higher in both the FFM and TBM conditions in 1MIN vs 30 sec, accompanied by a significantly lower fatigue index. HR was higher in both 30 sec protocols, with no differences in RPE and end [Bla] measures evident.
Brownstein et al. (2018) [10]	pre-PHV, n = 14, 12 ± 0.4	Running	Participants performed a repeated sprint sequence twice, comprising 10 × 30 m efforts (~5 sec)	30 sec, SS	AR: Recovery duration in SS significantly shorter (~12 sec). Mean sprint time faster in 30 sec, accompanied by smaller performance decrement. Mean and peakHR higher in SS.
	Post-PHV, n = 14, 14 ± 0.5				AR: Recovery duration in SS significantly shorter (~8 sec). Mean sprint time faster in 30 sec, accompanied by smaller performance decrement. Mean and peakHR higher in SS.
Gibson et al. (2017) [7]	n = 11, 14 ± 1	Running	Participants performed two repeated sprint assessment of 10 × 30 m sprint efforts (~5 sec)	30 sec, SS	AR: Training sequence shorter in SS, as SS recovery duration is significantly shorter (~10 sec). Mean sprint time significantly faster in 30 sec. No differences in peakHR, [Bla] and RPE.
Glaister et al. (2005) [14]	n = 25, 20.6 ± 1.5	Cycling	Participants completed 20 × 5 sec maximal sprints on a friction-braked cycle ergometer	10 sec, 30 sec	AR: Peak (~4%) and mean (~26%) power output higher in 30 sec, with lower measures of fatigue, RPE and end [Bla]. Contrary, VO_2, RER and HR measures were higher in 10 sec in both the work and recovery intervals.
Lee et al. (2011) [16]	n = 14, 18.7 ± 0.8	Cycling	Participants completed two intermittent sprint cycling tests (ISCTs), which were composed of 12 × 4 sec sprints. Tests were separated by 4 min active recovery	20 sec, 90 sec	AR: Peak and mean sprint power in both ISCTs higher in 90 sec vs 20 sec, with a lower fatigue index and RPE score. End [Bla] higher in 20 sec.
Ohya et al. (2013) [20]	n = 8, 25.5 ± 2.6	Cycling	Participants performed 10 maximal 5 sec sprints interspersed with either active recovery (ACT, cycling at 40% VO_2max) or passive recovery (PAS, sitting)	25 sec, 50 sec, 100 sec	AR: Mean and peak power decrement over sprints was lowest in 100 sec and, independent of ACT/PAS, inversely related to recovery time. Mean VO_2 and [Bla] were higher in 25 sec > 50 sec > 100 sec, whilst muscular reoxygenation was lower in 25 sec.
Padulo et al. (2015) [19]	n =17, 16 ± 0	Running	Participants completed three testing sessions, in which they performed six maximal 40 m shuttle sprints (20+20 m with a 180º change of direction, ~6 sec)	15 sec, 20 sec, 25sec	AR: Total sprint time was ~3% faster in 25 sec compared to 15 sec, and ~1.3% compared to 20 sec. [Bla] and fatigue index were highest in 15 sec, followed by 20 sec, and lowest in 25 sec.
Shi et al. (2018) [17]	n = 13, 26.2 ± 6.2	Cycling	Participants finished three RST protocols, consisting of 40 x 6 sec all-out sprints on a cycling ergometer (with resistance equating 7.5% body mass)	15 sec, 30 sec, 1MIN	AR: Peak and mean power output was higher in 1MIN compared to 15 sec and 30 sec, with a notable lower RPE. Accumulated time ≥ 80% and 90% VO_2max increased as recovery time decreased, however, for HR this was only evident in time ≥ 95% HRmax.
Sprint Interval Training					
Gosselin et al. (2012) [24]	n = 8, 23.1 ± 2.1	Running	Participants performed 2 different training protocols , in which they exercised at a workload corresponding to 90% VO_2max for 60 sec	30 sec, 1MIN	AR: Mean and peak VO_2 and HR significantly higher in 30 sec compared to 1MIN, with no differences in RPE. Both protocols failed to achieve 90% VO_2max.

Table 2: Continued

Study	Sample Size, Age	Modality	High Intensity Interval Training Protocol	Recovery Duration	Key Findings
Hazell et al. (2010) [22]	n = 48, 24 ± 3.2	Cycling	Participants completed 2 weeks of SIT (3 sessions a week), in which they performed 4-6 'all out' sprint of either 30 sec (G1) or 10 sec (G2 & G3), against 100 $g.kg^{-1}$. CON did not receive SIT	G1: 4MIN, G2: 4MIN, G3: 2MIN	AR: Peak and mean power output in sprints higher in G2 & G3, whilst G1 performed more total work. TA: Improvements in 5 km TT were similar between groups, whereas the increase in VO2max and mean and peak Wingate power output were higher in G1 & G2 compared to G3 and CON.
Iaia et al. (2015) [18]	n = 13, 18.5 ± 1	Running	Participants completed nine SIT sessions, which focussed on speed endurance production (SEP; n = 6) or speed endurance maintenance (SEM; n = 7). Both SEP and SEM consisted of 6–8 reps of 20 sec all-out sprints	SEP: 2MIN, SEM: 40 sec	AR: Mean running speed were higher in SEP sprints compared to SEM, with a lower decrement in speed across subsequent sprints. TA: SEM improved their 200-m sprint time, distance covered in Yo-Yo test increased 10.1% after SEP and 3.8% after SEM.
Kavaliauskas et al. (2015) [23]	G1, n = 8, 41± 12 G2, n = 8, 38 ± 7 G3, n = 8, 42 ± 6	Cycling	Participants completed a total of six SIT sessions over a two week period. The SIT protocol consisted of six 10-second "all-out" cycling efforts against a resistance equalling 7.5% of body weight. CON received no SIT	G1: 30 sec, G2: 80 sec, G3: 2MIN	AR: Average HR was greater in G1 compared with G3 for all training sessions, and was greater in G2 compared with G3 for training sessions 1 and 2. TA: All three training groups increased 3km TT to a similar extent. VO_2max increased in G1 & G2, but not in G3. Mean and peak Wingate power output increased after G2, whereas G3 only increased their mean power output.
McEwan et al. (2018) [8]	N = 14, 30 ± 7	Running	Participants performed 12 × 30 sec running intervals at a target intensity of 105% MAS.	30 sec, SS	AR: Mean recovery duration longer in SS (~21 sec). Relative time ≥ 105% MAS and mean running speed greater in SS, whereas time ≥ 90% HRmax was higher in 30 sec compared to SS . No differences in end [Bla] or RPE.
Toubekis et al. (2005) [21]	N = 16, 21.2 ± 0.6	Swimming	Participants completed eight repetitions of 25-m sprints (~15 sec), followed by a 50-m sprint test 6 min later. Recovery was either ACT or PAS.	45 sec, 2MIN	AR: Mean swimming velocity faster in PAS for both recovery durations, and faster in 2MIN compared to 45 sec with no differences in end [Bla]. 50-m sprint times were 2.4% faster in both ACT and PAS 2MIN conditions vs 45 sec.
Aerobic Interval Training					
Edge et al. (2013) [28]	N = 5, 21 ± 2	Cycling	Participants completed 6 × 120 sec intervals, on a power output corresponding to 92% VO_2max	1MIN, 3MIN	AR: Average HR in intervals higher in 1MIN vs 3MIN. 1MIN induced a greater end [Bla], H^+ and MLa content than 3MIN, while muscle PCr content was less after 1MIN.
Edge et al. (2013) [28]	G1, n = 6, 19 ± 1 G2, n = 6	Cycling	Participants performed a total 15 HIIT sessions over a 5 week period, consisting of 6 – 10 × 120 sec intervals at a workload of 92%-111% power output at VO_2max	G1: 1MIN, G2: 3MIN	TA: Significant increase in VO_2max, PPO and power output at lactate threshold, to a similar extent in both G1 and G2. Improvements in repeated sprint performance were similar.
Edwards et al. (2011) [5]	N = 11, 26 ± 7	Running	Participants completed a series of four (5 × 1000 m) track running sessions, each at the standardized perceived exertion of RPE 17.	SS_PR1, SS_PR2, HR130, W:R = 1	AR: Recovery significantly shorter in HR130, accompanied by a significant lower mean running velocity and greater fatigue index. Similar HR and end [Bla] between all experimental conditions.

Table 3: Continued

Study	Sample Size, Age	Modality	High Intensity Interval Training Protocol	Recovery Duration	Key Findings
Laurent et al. (2014) [26]	G1, n = 8, 20.8 ± 2.1 G2, n = 8, 21.9 ± 3.6	Running	Trained male (G1) and female (G2) runners completed three isoeffort (maximum sustainable intensity) training sessions, each comprising six 4 min interval	1MIN, 2MIN, 4MIN	AR: SS running velocity increased in both groups when longer recovery was available. Independent of recovery duration, mean VO_2, HR, [Bla] and RPE were similar across conditions in both G1 & G2. Relative exercise HR and VO_2 was higher in G2.
Laursen et al. (2002) [13]	G1, n = 8, 26 ± 6 G2, n = 9, 24 ± 7	Cycling	Participants performed eight AIT sessions over a 4 week period, comprising 8 intervals at Pmax for the duration of 60% Tlim	G1: W:R = 0.5, G2: 65HRmax	AR: G1 had a significantly greater total mean recovery time (~110 sec) between bouts compared with G2. Both groups completed ~64% of prescribed interval bouts. TA: Improvements in VO_2max, PPO, and 40 km TT were similar between groups.
Seiler & Hetlelid (2005) [6]	n = 9, 30 ± 4	Running	Participants performed three isoeffort (maximum sustainable intensity) training sessions, each comprising six 4 min intervals at a constant 5% treadmill incline.	1MIN, 2MIN, 4MIN, SS	AR: Higher running velocity in 2MIN (85% vVO_2max) and 4MIN (84% vVO_2max) vs 1MIN (83% vVO_2max). Higher mean VO_2 in 2MIN and 4MIN vs 1MIN. No differences in end [Bla], HR, or RPE.
Schoenmakers & Reed (2018) [9]	N =12, 34 ± 11	Running	Participants performed four isoeffort (maximum sustainable intensity) training sessions, each comprising six 4 min interval on a non-motorized treadmill	1MIN, 2MIN, 3MIN, SS_PR1	AR: Running velocity significantly higher in 3MIN compared to all other protocols, and higher in ssMIN vs 2MIN. No significant differences in RPE responses, time ≥ 90% and 95% VO_2max, or ≥ 90% and 95% HRmax
Smilioset al. (2018) [27]	N = 11, 22.1±1	Running	Participants executed, on three separate sessions, 4×4 min runs at 90% of MAS	2MIN, 3MIN, 4MIN	AR: Time ≥ 80 and 90% HRmax was higher in 2MIN and 3MIN compared to 4MIN, but did not differ for VO_2 measures. Peak HR and VO_2 were similar between conditions. RPE were higher in 2MIN and 3MIN vs 4MIN, as was 2MIN end [Bla]
Zavorsky et al. (1998) [29]	N = 12, 24.8 ± 5.1	Running	Participants performed three interval running workouts of 10 x 400 m on a predefined running speed	1MIN, 2MIN, 3MIN	AR: Mean HR significantly higher in 1MIN, but no differences in peakHR between conditions. RPE increased with decrease in recovery time.

Age is presented mean ± standard deviation

Note: 1MIN; 1 min recovery; 2MIN; 2 min recovery; 3MIN; 3 min recovery; 4MIN: 4 min recovery; ACT: active recovery; AIT: aerobic interval training; AR: Acute responses; [Bla]: blood lactate concentration; CON: control group; FFM: fat-free body mass; H^+: Hydrogen; HR: heart rate; HR130: recovery duration based on HR return to 130 bpm; HRmax: maximum heart rate; ISCTs: intermittent sprint cycling tests; MAS: maximal aerobic speed; MLa: muscle lactate; PAS: passive recovery; PCr: phosphocreatine; peakHR: peak heart rate; Pmax: minimal power output to elicit VO_2max; post-PHV: post peak height velocity; PPO: peak power output; pre-PHV: pre peak height velocity; RER: respiratory exchange ratio; RPE: ratings of perceived exertion; RST: repeated sprint training SIT: sprint interval training; SS: self-selected recovery duration; SS_PR1 & SS_PR2: self-selected recovery duration based on perceived readiness scale; SEM: speed endurance maintenance; SEP: speed endurance production; TA: Adaptations to a period of training; TBM: total body mass; Tlim: time to exhaustion at Pmax; TT: time trial; VO_2: oxygen consumption; VO_2max: maximum oxygen consumption vVO_2max: minimum running velocity to elicit VO_2max; W:R = 1: recovery duration equal to work interval duration