

Contents lists available at ScienceDirect

## Journal of Exercise Science &amp; Fitness

journal homepage: [www.elsevier.com/locate/jesf](http://www.elsevier.com/locate/jesf)

# Influence of recovery duration during 6-s sprint interval exercise on time spent at high rates of oxygen uptake

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## ARTICLE INFO

### Article history:

Received 30 August 2017

Received in revised form

24 November 2017

Accepted 3 January 2018

Available online 1 February 2018

### Keywords:

Exercise  
Sprint interval training  
Wingate sprints  
Aerobic fitness  
Teleoanticipation

## ABSTRACT

**Background/Objective:** This study examined whether time spent at high rates of oxygen consumption ( $\text{VO}_2$ ) during 6-s sprint interval exercises (SIE) is a function of recovery interval duration.

**Methods:** In a randomised crossover study, thirteen male endurance runners performed  $40 \times 6$ -s all-out sprints interspersed with 15-s, 30-s and 60-s passive recovery intervals (SIE<sub>15</sub>, SIE<sub>30</sub>, and SIE<sub>60</sub> trials respectively), and a work duration-matched Wingate-SIE ( $8 \times 30$ -s all-out sprints with 4-min passive recovery, SIE<sub>Win</sub> trial). The accumulated exercise time at  $\geq 80\%$ , 85%, 90%, 95% and 100% of  $\text{VO}_{2\text{max}}$ , and maximum heart rate ( $\text{HR}_{\text{max}}$ ) in the four trials were compared.

**Results:** During the 6-s SIEs, accumulated time spent at all selected high rates of  $\text{VO}_{2\text{max}}$  increased as recovery time decreased, whilst the SIE work rate decreased ( $p < .05$ ). In SIE<sub>Win</sub>, although the exercise lasted longer, the time spent at  $\geq 90\% \text{VO}_{2\text{max}}$  ( $74 \pm 16$  s) was significant less than that in SIE<sub>15</sub> ( $368 \pm 63$  s,  $p < .05$ ), yet comparable to that in SIE<sub>30</sub> ( $118 \pm 30$  s,  $p > .05$ ), and longer than that in SIE<sub>60</sub> ( $20 \pm 14$  s,  $p < .05$ ). The differences between the four trials in accumulated time at high percentages of  $\text{HR}_{\text{max}}$  were similar to those for  $\text{VO}_2$ , although the temporal characteristics of the increases in HR and  $\text{VO}_2$  during the SIEs were different.

**Conclusion:** In conclusion, the duration of the recovery interval in 6-s SIE protocols appears to be a crucial parameter when sprint interval training is prescribed to enhance aerobic capacity. Further, the SIE<sub>15</sub> protocol may represent a potential alternative to 30-s SIE<sub>Win</sub> in the development of time-efficient aerobic training intervention.

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## Introduction

High-intensity interval training appears to be more effective than continuous training in raising athletes' maximum oxygen uptake ( $\text{VO}_{2\text{max}}$ ) to the trainable limit, as it allows athletes to tolerate metabolic loading at or close to maximum for a prolonged period of time.<sup>1</sup> Moreover, brief interval training regimes consisting of sprint interval exercises (SIE) are often adopted by athletes to enhance their endurance performance, and by recreationally active persons to improve cardiometabolic health including aerobic fitness, because of its time efficient.<sup>2</sup> A typical SIE protocol

consisting of repeating four 30-s Wingate sprints interspersed with 4- or 4.5-min recovery intervals has been shown to tax the cardio-respiratory functional capacity of active individuals at above 80% during each interval.<sup>3</sup> It has been reported that Wingate-based sprint interval training elicits aerobic adaptations comparable to those resulting from continuous endurance training of moderate intensity, with training duration  $\geq 30$  min.<sup>4</sup>

Notwithstanding, a rather time-efficient interval training programme, in comparison to the Wingate regime, consisting of a further brief SIE protocol ( $10 \times 6$ -s cycle sprint against 7.5% body mass with 60-s passive recovery) have been shown to improve the aerobic capacity and endurance performance markedly in tri-athletes.<sup>5</sup> Moreover, when the exercise time and work-rest ratio of the Wingate-based and 6-s sprint interval training regimes were matched, the two training regimes produced similar improvements

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in self-paced 10-km time trial performance in active individuals.<sup>6</sup> However, whether the 6-s cycle SIE could be a potential alternative to the Wingate protocol in the development of time-efficient aerobic training intervention has not been investigated. It has been shown that in high-intensity interval training the load and duration of the work intervals determine the time spent at high percentages of  $\text{VO}_{2\text{max}}$ , a parameter which is crucial to eliciting aerobic adaptations to the training.<sup>7,8</sup> Although researchers continue to address the methodological variables of interval training that can affect the duration and degree of cardiovascular and metabolic stress that individuals can tolerate in a single session, it is not clear whether the time spent at high rates of  $\text{VO}_2$  ( $\geq 90\% \text{VO}_{2\text{max}}$ ) during a 6-s SIE protocol is a function of recovery duration *per se*. A recent study<sup>9</sup> reported that total exercise time above 80–95%  $\text{VO}_{2\text{max}}$  was comparable regardless of whether 2- or 4-min recovery intervals were used during an aerobic interval exercise (4 × 4-min runs at 90% of maximal aerobic velocity). However, such findings may not have implications for 6-s SIE protocols where the recovery interval is  $\leq 60$  s, as the haemodynamic and metabolic challenges, and the dominant sources of energy during the exercise, are apparently different from those in aerobic interval exercise.

The purpose of this study was to compare the time spent at high rates of  $\text{VO}_2$  ( $\geq 80\% \text{VO}_{2\text{max}}$ ) under three SIE protocols in which the load and duration of the work interval were identical (40 × 6 s all-out sprints) but the duration of the recovery interval duration varied (15-s, 30-s or 60-s passive recovery). The temporal characteristics of the increase in  $\text{VO}_2$  elicited by the three 6-s SIE protocols were also compared with those for a Wingate-based SIE protocol (8 × 30-s all-out sprints with 4-min passive recovery) in which the total work interval duration was matched to that of the four SIE protocols. It was hypothesised that time spent at high rates of  $\text{VO}_2$  during a single bout of 6-s SIE would be a function of recovery interval duration, and that the time efficiency of the 6-s SIE protocol for inducing strenuous aerobic demand was higher than that of the work duration-matched Wingate-based SIE protocol.

## Method

### Research design

In this study, participants performed four single SIE sessions on a Wingate testing cycle ergometer (Monark 894 E, Stockholm, Sweden) on separate days. In three of the SIEs, participants performed 40 × 6-s all-out sprints interspersed with 15-s (SIE<sub>15</sub>), 30-s (SIE<sub>30</sub>) or 60-s (SIE<sub>60</sub>) of passive recovery. The remaining session was a Wingate-based SIE consisting of 8 × 30-s all-out sprints with 4-min passive recovery intervals (SIE<sub>Win</sub>), performed on the same ergometer. In all SIEs, the ergometer resistance was set at 7.5% of the participant's body mass. The order in which the four SIE trials were performed was counterbalanced and the assignment of participants to orders was random. The accumulated time spent at  $\geq 80\%$ , 85%, 90%, 95% and 100% of  $\text{VO}_{2\text{max}}$  and  $\text{HR}_{\text{max}}$  were compared across the four trials.

### Participants

Thirteen male athletes [age:  $26.2 \pm 6.2$  yrs, height:  $172.8 \pm 7.3$  cm, weight:  $60.8 \pm 3.8$  kg,  $\text{VO}_{2\text{max}}$ :  $61.3 \pm 9.1$  ml  $\text{min}^{-1}$   $\text{kg}^{-1}$ , maximum heart rate ( $\text{HR}_{\text{max}}$ ):  $164.9 \pm 8.1$  beat  $\cdot \text{min}^{-1}$ ] who had been engaged in long-distance running for over five years participated voluntarily. The sample size was computed based on the formula  $n = \sigma^2 (-z_0 + z_1)^2 / (\mu_0 - \mu_1)^2$ ,<sup>10</sup> where the mean differences ( $\mu_0 - \mu_1$ ) and standard deviation ( $\sigma$ ) were estimated from pilot testing results. Alpha and power level were set at 0.05 and 0.9, respectively.  $z_0$  is the critical value for effect size under the null

distribution and  $z_1$  is the critical value associated with the alternative distribution.

The participants had no familial history of cardiovascular disease and were not taking any cardiovascular medication. Moreover, none had prior experience of nutritional or ergogenic supplements. Following an explanation of the purpose and requirements of the study, participants gave written informed consent. Study approval was obtained from the Research Ethics Board, University of Macau.

### Preliminary and familiarization trials

First, the participants' physical characteristics were measured. Body mass was measured using a bioelectrical impedance analyser (InBody 720, Biospace, Tokyo, Japan) and used to determine the resistance used in subsequent SIE tests. Next, participants were familiarised with the all-out SIE protocols over two days.

During the experimental period, all participants were asked to maintain their daily activity as well as their training load and volume, and avoid altering their eating habits. Participants were asked to refrain from eating and participation in strenuous physical activity for, respectively, at least 2 h and one day before trials. All experimental trials were performed under identical, controlled laboratory conditions (temp: 22 °C, RH: 75%). All trials were scheduled to occur at the same time of day and were separated by at least five days.

### Graded exercise test

The test was carried out on an electronically braked cycle ergometer (Monark 839E, Stockholm, Sweden). Following a 3-min warm-up at 25 W, the test started with an initial work rate of 50 W. Participants were asked to maintain a pedalling cadence of 60 rpm, and the power was increased by 25 W every minute, until volitional exhaustion. Metabolic data were recorded during the test using the Metamax 3B gas analysis system (Cortex, Leipzig, Germany) and HR was monitored using a Polar HR sensor (H3, Finland). Ten-s means were calculated and the highest values were the maximal. Participants were assumed to have achieved their  $\text{VO}_{2\text{max}}$  when they met any three of the following criteria: 1) apparent exhaustion; 2) plateau in  $\text{VO}_2$ ,  $\Delta \text{VO}_2 < 2.1$  ml  $\text{kg}^{-1} \cdot \text{min}^{-1}$  regardless of increase in workload; 3)  $\text{HR}_{\text{max}} > 90\%$  of the predicted maximum (220 - age); 4) respiratory exchange ratio  $\geq 1.15$ .

### Sprint interval exercise test

All SIE trials consisted of a standardised warm-up exercise consisting of 5-min cycling exercise at 60 W, five 6-s cycle sprints at progressively increasing speed and 5-min of stretching. During the SIE recovery intervals, participants remained seated but stationary on the cycle ergometer. During the last 5 s of each recovery interval participants were given a 5-s countdown and in the last 2 s they were instructed to accelerate from a stationary start with minimum friction applied to the flywheel. At the start of the work interval, the preset load was applied instantaneously with an electromagnetic device. Participants remained seated whilst cycling and their feet were secured to the pedals using toe clips. Verbal encouragement was given throughout each sprint to ensure all-out effort. Power output in each sprint was recorded using Monark Anaerobic Test Software (3.0, Stockholm, Sweden) with a preset sampling rate of 50 Hz.  $\text{VO}_2$  and HR were recorded throughout the exercise using the Metamax 3B system and Polar HR sensor, respectively. Immediately after exercise, participants used the Borg scale (6–20) to provide ratings of perceived exertion (RPE). Five-s  $\text{VO}_2$  means were plotted against exercise time. Horizontal lines at 80%, 85%, 90%, 95%, and 100% of  $\text{VO}_{2\text{max}}$  were drawn on the graph. The total time spent at

each VO<sub>2</sub> level was taken as the number of time points at or above the relevant horizontal line  $\times$  5 s. A similar procedure was used to calculate total time spent at each HR level.

### Statistical analyses

A Shapiro-Wilk test revealed that all variables were normally distributed. Repeated measures ANOVA was used to examine between-level and between-trial differences. Post-hoc analyses were carried out using the Newman-Keuls test. Cohen's *d* was calculated to reveal the effect size of selected mean differences. The level of significance in all statistical test was set at  $p < .05$ . Data were expressed as mean  $\pm$  SE.

### Results

Table 1 shows peak and mean power output, post-SIE RPE and total time spent at selected percentages of VO<sub>2max</sub> and HR<sub>max</sub> for the four SIEs. Peak and mean power output were highest in the SIE<sub>60</sub> trials and decreased progressively with recovery interval duration in the SIE<sub>30</sub> and SIE<sub>15</sub> trials ( $p < .05$ , Cohen's  $d \geq 1.18$ ). The lowest power output occurred in the SIE<sub>Win</sub> trials. However, post-SIE RPE was similar in the SIE<sub>30</sub>, SIE<sub>15</sub>, and SIE<sub>Win</sub> trials ( $p > .05$ ), whereas it was lower in SIE<sub>60</sub> trials ( $p < .05$ ).

In SIE<sub>15</sub> trials more time was spent at all selected high percentages of VO<sub>2max</sub> than in other trials ( $p < .05$ , Cohen's  $d \geq 0.99$ ). In contrast, less time was spent at all selected high percentages of VO<sub>2max</sub>, except  $\geq 100\%$  VO<sub>2max</sub>, in SIE<sub>60</sub> trials than in other trials ( $p < .05$ , Cohen's  $d \geq 0.87$ ). In SIE<sub>30</sub> more time was spent at  $\geq 80\%$  VO<sub>2max</sub> and  $\geq 85\%$  VO<sub>2max</sub> than in SIE<sub>Win</sub> ( $p < .05$ , Cohen's  $d \geq 0.69$ ), but the total times spent at other percentages of VO<sub>2max</sub> were similar ( $p > .05$ ).

More time was spent at  $\geq 80\%$  HR<sub>max</sub> in the SIE<sub>30</sub> and SIE<sub>60</sub> trials than in other trials ( $p < .05$ , Cohen's  $d \geq 0.94$ ). More time was spent at  $\geq 85\%$  HR<sub>max</sub> in SIE<sub>30</sub> trials than other trials, and less time in SIE<sub>Win</sub> trials ( $p < .05$ , Cohen's  $d \geq 0.56$ ). More time was spent at  $\geq 90\%$  HR<sub>max</sub> and  $\geq 95\%$  HR<sub>max</sub> in the SIE<sub>15</sub> and SIE<sub>30</sub> trials than in other trials ( $p < .05$ , Cohen's  $d \geq 0.70$ ). Similar results were also found in time spent at  $\geq 100\%$  HR<sub>max</sub> ( $p < .05$ , Cohen's  $d \geq 0.52$ ) while the difference between SIE<sub>30</sub> and other trials was not significant ( $p > .05$ ).

**Table 1**  
The peak and mean power output, RPE, and the temporal characteristics of the increase in VO<sub>2</sub> and heart rate of the SIE<sub>15</sub>, SIE<sub>30</sub>, SIE<sub>60</sub>, SIE<sub>Win</sub> are shown.

	SIE <sub>15</sub>	SIE <sub>30</sub>	SIE <sub>60</sub>	SIE <sub>Win</sub>
Peak power (W)	649 $\pm$ 109*	768 $\pm$ 96 <sup>bc</sup>	883 $\pm$ 138 <sup>c</sup>	615 $\pm$ 92
Mean power (W)	492 $\pm$ 81*	576 $\pm$ 70 <sup>bc</sup>	652 $\pm$ 97 <sup>c</sup>	439 $\pm$ 56
RPE	19.0 $\pm$ 0.5 <sup>b</sup>	18.2 $\pm$ 0.7 <sup>b</sup>	16.1 $\pm$ 1.1	18.3 $\pm$ 0.7 <sup>b</sup>
Exercise time (s) $\geq$				
80% VO <sub>2max</sub>	557 $\pm$ 69*	317 $\pm$ 66 <sup>bc</sup>	47 $\pm$ 22 <sup>c</sup>	151 $\pm$ 25
85% VO <sub>2max</sub>	470 $\pm$ 71*	188 $\pm$ 40 <sup>bc</sup>	30 $\pm$ 19 <sup>c</sup>	109 $\pm$ 20
90% VO <sub>2max</sub>	368 $\pm$ 63*	118 $\pm$ 30 <sup>b</sup>	20 $\pm$ 14 <sup>c</sup>	74 $\pm$ 16
95% VO <sub>2max</sub>	271 $\pm$ 57*	79 $\pm$ 24 <sup>b</sup>	12 $\pm$ 10 <sup>c</sup>	43 $\pm$ 10
100% VO <sub>2max</sub>	179 $\pm$ 49*	40 $\pm$ 16	8 $\pm$ 7	18 $\pm$ 7
Exercise time (s) $\geq$				
80% HR <sub>max</sub>	836 $\pm$ 19	1324 $\pm$ 52 <sup>a</sup>	1339 $\pm$ 210 <sup>a</sup>	660 $\pm$ 116
85% HR <sub>max</sub>	809 $\pm$ 30 <sup>c</sup>	1155 $\pm$ 83 <sup>ab</sup>	838 $\pm$ 205 <sup>c</sup>	450 $\pm$ 92
90% HR <sub>max</sub>	777 $\pm$ 43 <sup>bc</sup>	863 $\pm$ 127 <sup>bc</sup>	433 $\pm$ 185	265 $\pm$ 59
95% HR <sub>max</sub>	681 $\pm$ 61 <sup>bc</sup>	486 $\pm$ 127 <sup>bc</sup>	180 $\pm$ 114	119 $\pm$ 33
100% HR <sub>max</sub>	402 $\pm$ 82 <sup>bc</sup>	210 $\pm$ 120	69 $\pm$ 50	28 $\pm$ 15

RPE = rating of perceived exertion; VO<sub>2max</sub> = maximal oxygen uptake; HR<sub>max</sub> = maximal heart rate.

\*Significantly different from SIE<sub>30</sub>, SIE<sub>60</sub> and SIE<sub>Win</sub> ( $p < .05$ ).

<sup>a</sup> Significantly different from SIE<sub>15</sub> and SIE<sub>Win</sub> ( $p < .05$ ).

<sup>b</sup> Significantly different from SIE<sub>60</sub> ( $p < .05$ ).

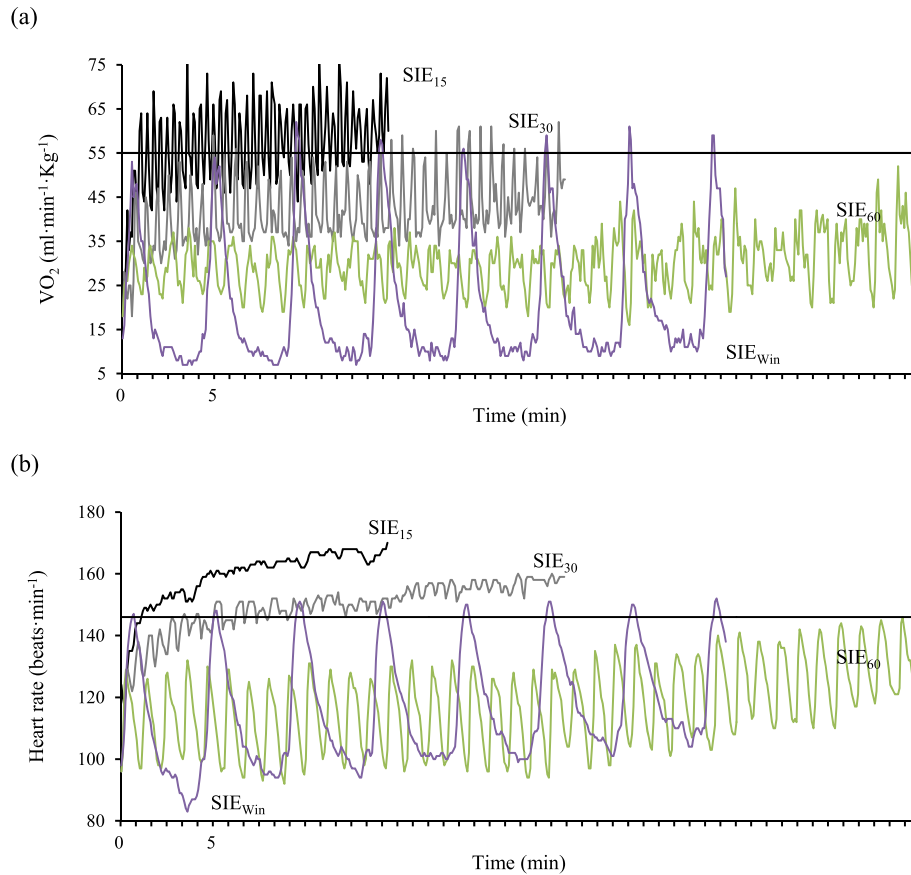
<sup>c</sup> Significantly different from SIE<sub>Win</sub> ( $p < .05$ ).

### Discussion

To the best of our knowledge, this is the first study to compare the temporal characteristics of the increase in VO<sub>2</sub> across three 6-s SIE protocols with different recovery intervals and a work duration-matched Wingate-based SIE protocol. The novel findings are: (a) altering the recovery interval (15 s; 30 s; 60 s) used in the 6-s SIE protocol altered the total time spent at high percentages of VO<sub>2</sub> ( $\geq 90\%$  VO<sub>2max</sub>); (b) the brief duration of the work and recovery intervals in the 6-s SIE protocol resulted in longer time spent at high percentages of VO<sub>2max</sub> relative to a SIE<sub>Win</sub> protocol; (c) the temporal characteristics of the increase in HR during the four SIEs do not correspond to those of the increase in VO<sub>2</sub>, suggesting that the HR response may not be a precise reflection of the metabolic stress imposed by SIE.

During the three 6-s SIEs in which participants were required to exert all-out effort in each sprint reducing the recovery-interval duration markedly increased VO<sub>2</sub> during both work intervals and recovery intervals, and hence accumulated time at  $\geq 80\%$  VO<sub>2max</sub>; this was matched by decreases in peak and mean power output (Table 1). These findings contrast with those reported previously for high-intensity aerobic interval exercise,<sup>9</sup> and indicate that the extent to which participants maximise their use of their functional aerobic capacity during SIEs is partly determined by the length of the recovery interval, whilst the metabolic stress during SIE appears to increase incrementally as recovery interval duration decreases. It was noted that the longer the recovery intervals during SIE, the greater the decrease in VO<sub>2</sub> relative to the preceding work interval. Although the lower VO<sub>2</sub> might have resulted in faster VO<sub>2</sub> kinetics at the beginning of the subsequent exercise bout,<sup>11</sup> the extent of the increase in VO<sub>2</sub> during the exercise bouts of the three SIEs were not conformed. This was reflected in peak VO<sub>2</sub> in work intervals, which was consistently lower during the SIE<sub>60</sub> trials than in the SIE<sub>30</sub> and SIE<sub>15</sub> trials, with peak VO<sub>2</sub> being highest in SIE<sub>15</sub> trials (Fig. 1a). However, peak and mean power output were higher in the SIE<sub>60</sub> trials than the SIE<sub>15</sub> and SIE<sub>30</sub> trials (Table 1). In fact, restoration of power output during repeated supramaximal sprint exercise (<10 s) is mainly reliant on the rate of PCr resynthesis; the halftime for PCr turnover following a sprint is 20–30 s and this increases to 56 s as a result of sluggish blood flow in active muscles during passive recovery between sprints.<sup>12,13</sup> It was therefore reasonable to postulate that the longer recovery interval during SIE<sub>60</sub> trials would result in greater PCr availability than in SIE<sub>15</sub> and SIE<sub>30</sub> trials, enabling participants to work harder during the exercise intervals.<sup>14</sup> As the relatively short recovery duration in SIE<sub>15</sub> and SIE<sub>30</sub> limits resynthesis of PCr, there is presumably greater reliance on aerobic energy in the repeated sprints. This was supported by our current findings that the VO<sub>2</sub> spectrum in response to work and recovery intervals during the 6-s SIE (Fig. 1a) increased as recovery duration decreased; and this was concomitant with the decrease in the SIE power output (Fig. 2).

It is generally agreed that the optimal interval training stimulus for improving peak aerobic function is one that allows participants to exercise above 90% VO<sub>2max</sub> over an accumulated total of several minutes, preferably 5–10 min per session.<sup>9,15</sup> Of the three SIE protocols, the SIE<sub>15</sub> protocol appeared to be most effective in ensuring that participants exercised at intensities corresponding to  $\geq 90\%$  VO<sub>2max</sub> for more than 6 min in total; this several times higher than achieved under the SIE<sub>30</sub> and SIE<sub>60</sub> protocols. It is plausible to suggest that accumulated high-intensity exercise time under the SIE<sub>30</sub> and SIE<sub>60</sub> protocols could be extended by increasing the repetitions of the sprint in each protocol. However, lengthening an SIE protocol would compromise its time-efficiency as a method of improving aerobic function. It also deviates from a recent report on development of health interventions which recommended that the



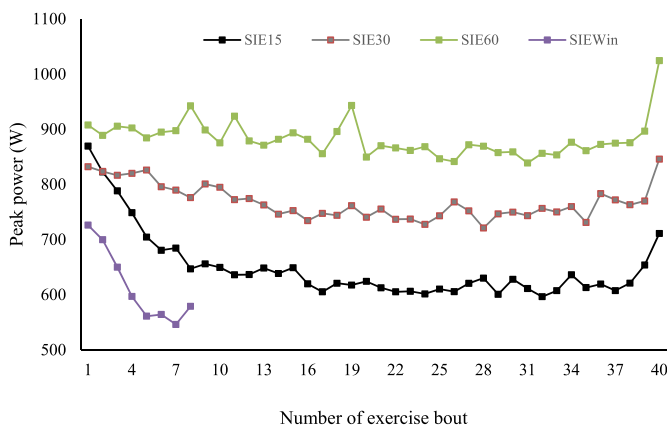
**Fig. 1.** The time courses of changes in (a)  $\text{VO}_2$  and (b) heart rate of a typical participant in  $\text{SIE}_{15}$ ,  $\text{SIE}_{30}$ ,  $\text{SIE}_{60}$ , and  $\text{SIE}_{\text{Win}}$ . Solid horizontal line is 90% of corresponding measured maximum value.

involvement of minimal sprint durations and repetitions should be a top priority for the future development of the sprint interval training for health benefit.<sup>16</sup> Based on the data presented here the best SIE protocol for potentially development of training intervention to improve aerobic capacity, on grounds of time efficiency, is the 14-min  $\text{SIE}_{15}$ , under which ~45% of exercise time was spent at intensities approaching  $\text{VO}_{2\text{max}}$ .

Four to ten 30-s Wingate sprints interspersed with 4-min recovery intervals was considered as a classic sprint interval training protocol that is associated with various central and

peripheral aerobic adaptations.<sup>15</sup> However, less time was spent at  $\geq 90\%$   $\text{VO}_{2\text{max}}$  (~1.2 min) in  $\text{SIE}_{\text{Win}}$  than in  $\text{SIE}_{15}$  trials. Moreover, the peak power output in the first  $\text{SIE}_{\text{Win}}$  work interval ( $726 \pm 147$  W) was lower than the corresponding power output in the  $\text{SIE}_{15}$  trial ( $870 \pm 180$  W), despite the fact that participants were requested to exert all-out effort in all sprints in both trials. This discrepancy in physical exertion is consistent with earlier findings of teleoanticipation in all-out sprint cycle exercise.<sup>17</sup> It has been reported that an all-out pacing strategy is only found in repeated sprint cycles if the duration of a single exercise bout is no more than 15 s; dampening of power output occurs with work intervals of 30 s and 45 s.<sup>17</sup> The lower power output achieved in the first 30-s sprint in the  $\text{SIE}_{\text{Win}}$  trial (Table 1) might reflect participants' unconscious adoption of a pacing strategy in an attempt to complete the  $\text{SIE}_{\text{Win}}$  protocol within their biomechanical and metabolic limits.<sup>18</sup> Together with the decline in metabolic rate during the prolonged recovery intervals of the  $\text{SIE}_{\text{Win}}$  protocol, this may partly explain the relatively short total time spent at high percentages of  $\text{VO}_2$ , relative to the  $\text{SIE}_{15}$  trials. Performance of the  $\text{SIE}_{\text{Win}}$  protocol, including recovery time, took >30 min. The lengthy  $\text{SIE}_{\text{Win}}$  protocol does not, however, appear to be more effective than 6-s  $\text{SIE}_{15}$  protocol in imposing metabolic stress on the oxidative system.

The temporal characteristics of the increase in HR during the four SIE trials were not matched by the pattern in increases in  $\text{VO}_2$  (Table 1). In  $\text{SIE}_{15}$  and  $\text{SIE}_{30}$  trials, participants' HR increased to >80%  $\text{HR}_{\text{max}}$  as soon as they started the first sprint and remained at that level throughout the trial (Fig. 1b). In fact more than 90% and 60% of work time was spent at  $\geq 90\%$   $\text{HR}_{\text{max}}$  during the  $\text{SIE}_{15}$  and



**Fig. 2.** The changes in group mean of peak power output during the repeated sprint cycle exercises in  $\text{SIE}_{15}$ ,  $\text{SIE}_{30}$ ,  $\text{SIE}_{60}$ , and  $\text{SIE}_{\text{Win}}$ .



SIE<sub>30</sub> trials respectively, which is inconsistent with the amount of work time spent at  $\geq 90\%$  VO<sub>2</sub>. Similar discrepancies between the temporal characteristics of the increases in HR and in VO<sub>2</sub> in participants doing aerobic interval exercise have been reported previously.<sup>9</sup> Such findings suggest that the HR response to high-intensity interval exercise may not precisely reflect the immediate stress on participants' oxidative systems. Moreover, the strenuous cardiovascular stress elicited from all-out sprints during the 6-s SIEs, which did not release effectively in brief recovery intervals, potentiates the risk of cardiac distress that sedentary and unfit individuals should participate in it with cautions.

## Conclusions

This study found that reducing the recovery interval used in a 6-s SIE protocol (SIE<sub>60</sub>; SIE<sub>30</sub>; SIE<sub>15</sub>) increased the total exercise time spent at high percentages of VO<sub>2max</sub> ( $\geq 90\%$  VO<sub>2max</sub>), suggesting that the length of the recovery interval is a crucial parameter when 6-s SIE protocols are used to improve aerobic capacity. Moreover, the SIE<sub>15</sub> protocol, which involves shorter exercise and recovery intervals, resulted in longer time spent at high percentages of VO<sub>2max</sub> relative to the SIE<sub>win</sub> protocol, implying that the SIE<sub>15</sub> protocol is a potential alternative to 30-s SIE<sub>win</sub> in the development of time-efficient aerobic training intervention. Nevertheless, it is worth noting that the current findings of the metabolic and cardiovascular responses resulting from the SIE protocols were obtained from the trained participants who were accustomed to rigorous workouts and associated intense physical stress. Cautions should be exercised in untrained populations participating in the repeated-sprint protocol, taking into account the individual's cardio-respiratory fitness.

## Acknowledgements

The study was supported by a research grant from Macao Polytechnic Institute (RP/ESEFD-02/2012).

## Appendix A. Supplementary data

Supplementary data related to this article can be found at <https://doi.org/10.1016/j.jesf.2018.01.001>.

## References

1. Londeree BR. Effect of training on lactate/ventilatory thresholds: a meta analysis. *Med Sci Sports Exerc.* 1997;29:837–843.
2. Gibala MJ, Andrew M, Jones AM. Physiological and performance adaptations to high-intensity interval training. *Nestle Nutr Inst Workshop Ser.* 2013;76:51–60.
3. Freese EC, Gist NH, Cureton KJ. Physiological responses to an acute bout of sprint interval cycling. *J Strength Condit Res.* 2013;27:2768–2773.
4. Gist NH, Fedewa MV, Dishman RK, et al. Sprint interval training effects on aerobic capacity: a systematic review and meta-analysis. *Sports Med.* 2014;44:269–279.
5. Jakeman J, Adamson S, Babraj J. Extremely short duration high-intensity training substantially improves endurance performance in triathletes. *Appl Physiol Nutr Metabol.* 2012;37:976–981.
6. Lloyd Jones MC, Morris MG, Jakeman JR. Impact of time and work:rest ratio matched sprint interval training programmes on performance: a randomised controlled trial. *J Sci Med Sport.* 2017;S1440–2440:30361–30364.
7. Midgley AW, McNaughton LR, Wilkinson M. Is there an optimal training intensity for enhancing the maximal oxygen uptake of distance runners?: empirical research findings, current opinions, physiological rationale and practical recommendations. *Sports Med.* 2006;36:117–132.
8. Wakefield BR, Glaister M. Influence of work-interval intensity and duration on time spent at a high percentage of VO<sub>2max</sub> during intermittent supramaximal exercise. *J Strength Condit Res.* 2009;23:2548–2554.
9. Smilios I, Myrkos A, Zafeiridis A, et al. The effects of recovery duration during high-intensity interval exercise on time spent at high rates of oxygen consumption, oxygen kinetics and blood lactate. *J Strength Condit Res.* 2017. <https://doi.org/10.1519/JSC.0000000000001904>. Online.
10. Toothaker LE, Miller L. *Introductory Statistics for the Behavioral Sciences*. second ed. Pacific Grove, CA: Brooks-Cole Publishing Co.; 1996.
11. DiMenna FJ, Wilkerson DP, Burnley M, et al. Influence of priming exercise on pulmonary O<sub>2</sub> uptake kinetics during transitions to high-intensity exercise from an elevated baseline. *J Appl Physiol.* 2008;105:538–546.
12. Bogdanis GC, Nevill ME, Boobis LH, et al. Recovery of power output and muscle metabolites following 30 s of maximal sprint cycling in man. *J Physiol.* 1995;482(Pt 2):467–480.
13. Harris RC, Edwards RHT, Hultman E, et al. The time course of phosphocreatine resynthesis during recovery of the quadriceps muscle in man. *Pflügers Archiv.* 1976;367:137–142.
14. Glaister M, Stone MH, Stewart AM, et al. The influence of recovery duration on multiple sprint cycling performance. *J Strength Condit Res.* 2005;19:831–837.
15. Buchheit M, Laursen PB. High-intensity interval training, solutions to the programming puzzle: Part I: cardiopulmonary emphasis. *Sports Med.* 2013;43:313–338.
16. Vollaard NB, Metcalfe RS. Research into the health benefits of sprint interval training should focus on protocols with fewer and shorter sprints. *Sport Med.* 2017;47:2443–2451. Online.
17. Wittekind AL, Micklewright D, Beneke R. Teleoanticipation in all-out short-duration cycling. *Br J Sports Med.* 2011;45:114–119.
18. Ulmer HV. Concept of an extracellular regulation of muscular metabolic rate during heavy exercise in humans by psychophysiological feedback. *Experientia.* 1996;52:416–420.