

The influence of short-term high intensity interval training on endurance performance in highly trained endurance athletes

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Introduction

Coaches of endurance athletes are well aware that high intensity interval training (HIT) enhances endurance performance. However, little scientific information is available concerning the optimal type of HIT program (i.e. optimal intensity, duration, and recovery) that produces the greatest improvement in endurance performance in highly trained athletes. Some work pertaining to HIT program optimization that has been completed in highly trained runners has used the minimal running speed that elicits VO_{2max} ($v_{VO_{2max}}$) as the optimal run intensity, with specific fractions (50-70%) of the time to exhaustion at $v_{VO_{2max}}$ (T_{max}) as the interval duration (3, 10). However, the application of these methods has yet to be examined in cyclists. In fact, only one study has examined HIT program optimization in endurance trained cyclists (11). The effects of five different HIT programs performed twice per week for three consecutive weeks on the rate of performance improvements were investigated in 20 endurance-trained cyclists. Interestingly, two markedly different HIT programs produced similar improvements in peak power output (PPO) and 40-km time trial (TT_{40}) performance. One of these programs involved “aerobic” type intervals (8 x 4 min at 85% PPO, 90 s recovery) that have improved performance previously (6, 11-13). However, a comparable enhancement of performance was obtained using repeated supramaximal sprinting (12 x 30 s at 175% PPO, 4.5 min recovery). The fact that repeated “anaerobic” sprinting could improve “aerobic” endurance performance is an intriguing finding, as supramaximal sprinting is not traditionally used for HIT program prescription for endurance events lasting ~1 h. However, the sample size in this study was small (N=4 per group), and the authors noted that the response to the training protocols was variable (11). In addition to the alteration of HIT intensities, very little work has attempted to optimize the recovery following HIT work bouts (14).

Thus, the purpose of the present study was to investigate the effects of different HIT protocols, performed over two and four weeks, on the endurance performance of highly trained cyclists. The effects of more traditional “aerobic” intervals were compared to those of repeated supramaximal sprinting and to a control group that maintained their normal base-training throughout this time period. Of interest also, was the influence of recovery between HIT bouts on performance changes.

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Methods

Subjects: 41 highly-trained male cyclists (age = 25.1 ± 5.8 yr; height = 180 ± 5 cm; mass = 75.3 ± 7.2 kg; sum of five skinfolds = 42.2 ± 15.1 ; $VO_{2peak} = 64.5 \pm 5.2$ ml \cdot kg $^{-1}$ \cdot min $^{-1}$) were recruited for this study. Subjects had been training for and competing in cycling events on a regular basis for 5.9 ± 4.3 yr, and average cycle training distance maintained during the study was (285 ± 95 km \cdot wk $^{-1}$). All subjects gave their written informed consent to participate in this study, which was approved by the Medical Research Ethics Committee of The University of Queensland.

Preliminary Testing:

Preliminary testing was conducted during the off-season and pre-competitive phase of the athletes yearly training program. All subjects were asked to keep a detailed training diary during this time. For three consecutive weeks, athletes were asked to report to the laboratory three times each week to perform 1) a progressive exercise test to determine peak oxygen consumption (VO_{2peak}), 2) a time to exhaustion test (T_{max}) at the VO_{2peak} power output (P_{max}), and 3) a 40-km time trial (TT_{40}) on their own road bicycle mounted to a stationary windtrainer. The first week was considered a familiarization week, and the results obtained during weeks two and three were used to measure the coefficient of variation (CV) of the baseline measures. Subjects reported to a controlled environmental laboratory condition ($\sim 21^\circ\text{C}$, 40-60%RH, 760-770 mm Hg) at the same time of day for all tests. The same encouragement was given during each test, and on all occasions, incremental power output, speed, and/or exercise time was blinded to the athlete. Before all tests, athletes were asked to keep their eating habits constant, to report to the laboratory at least two hours post-prandial, and to drink water during this time to maintain euhydration. Anthropometric measurements including sum of five skinfolds (biceps, triceps, subscapular, supraspine, and abdominal) was measured in duplicate by the same investigator using Marpen skinfold calipers.

Progressive Exercise Test:

VO_{2peak} was determined on an electronically braked cycle ergometer (Lode Excalibur Sport, Quinton) modified with clip-in pedals and low profile racing handlebars, using an incremental test involving an initial workload of 100W, followed by 15 W increments every 30 s until volitional fatigue. Peak power output (PPO) was defined as the final completed incremental stage. Expired air was analyzed for $F_{E}O_2$ and $F_{E}CO_2$ every 30 s during exercise using Ametek gas analyzers (SOV S-3A11 and COV CD3A, Pittsburgh, PA), and ventilation was recorded every 30 s using

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Time To Volitional Fatigue At 150% Of Peak Power Output (TF_{150}):

Fifteen minutes immediately following the progressive exercise test, subjects performed a ride to volitional fatigue at 150% of the PPO obtained during the VO_{2peak} test (TF_{150}). TF_{150} power output calculated pre-HIT was used throughout the reassessments despite the fact that PPO may have been altered. Volitional fatigue was defined as an inability to maintain pedaling cadence above $60 \text{ rev}\cdot\text{min}^{-1}$.

Time To Exhaustion at P_{max} (T_{max}):

P_{max} was calculated from the progressive exercise test and defined as the minimal power output that elicited a VO_2 reading that was within $2.1 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ of the previous reading, despite an increase in workload (2). The T_{max} test was conducted at least 24 h following the VO_{2peak} test. Following a 5 min warm-up at 100-250 W, subjects were timed for the duration at which they could maintain P_{max} with a cadence above $60 \text{ rev}\cdot\text{min}^{-1}$.

Laboratory Simulated 40-Km Time Trial (TT_{40}):

A laboratory simulated TT_{40} was completed on the subjects own road bicycle mounted to a stationary windtrainer (Cateye – Cycosimulator CS-1000), according to methods that have previously been described (9). The total time to complete 40-km was recorded for the calculation of average speed.

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Subjects were assigned to groups based firstly on their TT_{40} performance, and secondly, on their VO_{2peak} , in order to create equal groups. All HIT groups trained twice per week for four weeks, and were reassessed after two and four weeks of HIT. Group 1 (G_1) completed eight intervals at P_{max} , for a duration equal to $60\% T_{max}$, with a 1:2 recovery ratio. Group 2 (G_2) performed the same work intervals as G_1 , except that recovery time was based on heart rate (HR) returning to $65\% HR_{peak}$. Group 3 (G_3) completed 12x30s bouts at 175% of PPO, separated by 4.5 min of recovery. The control group (CON) was reassessed over the same timeline and were asked to maintain their regular base-training program (low intensity in nature). Two subjects from G_1 , and one subject from G_2 were eliminated from the data analysis due to illness or failure to comply with the training regime, leaving 8 subjects in G_1 , 9 subjects in G_2 , 10 subjects in G_3 , and 11 subjects in CON for the final analysis.

Statistics

Using the standard deviation from TT_{40} in previous research (6, 12, 13), it was calculated that 10 subjects per group would be required to obtain an effect size of 0.80. A one-way ANOVA examined differences between the groups prior to the HIT intervention. A 4 x 2 (Group x Time) repeated measures ANOVA compared changes in the dependent measures with training between groups. Dunnett's *Post Hoc* comparisons were used to determine whether the HIT groups improved significantly more than the control group, while Tukey's *Post Hoc* compared differences between HIT groups. All statistics were run on SPSS 10.0 for Windows, and alpha was set at 0.05. All data is expressed as 'x ± SD'.

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Results

Figures 1-3. The effects of two and four weeks of different high-intensity interval training (HIT) programs (G_1 , G_2 , G_3 ; see text for details) compared to controls (CON) on 40-km time trial (TT_{40}) performance (Figure 1), peak power output (PPO) (Figure 2), and peak oxygen uptake (VO_{2peak}) (Figure 3).

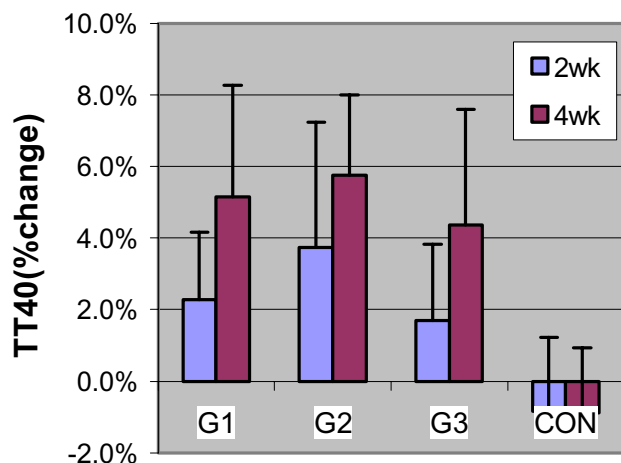


Figure 1. G_1 , G_2 , and G_3 improved significantly more than controls (CON) ($P < 0.05$).

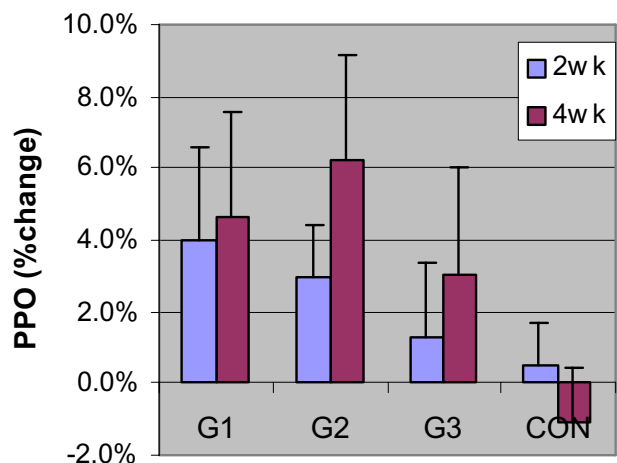


Figure 2. G_1 , G_2 , and G_3 improved significantly more than controls (CON) ($P < 0.05$), while G_2 improved significantly more than G_3 ($P < 0.05$).

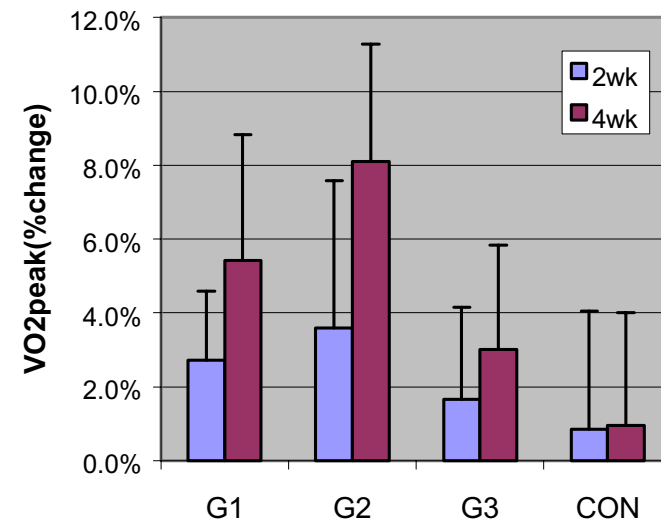


Figure 3. G_1 and G_2 improved significantly more than CON ($P < 0.05$), while G_2 improved significantly more than G_3 ($P < 0.05$).

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The coefficient of variation (CV) calculated from the preliminary tests on the dependant measures of TT_{40} , VO_{2peak} , PPO, TF_{150} , and T_{max} were found to be 0.9%, 1.8%, 2.1%, 8.2% and 11.9%, respectively. There were no statistical differences between any of the groups on the dependant measures prior to the HIT intervention. There was no significant difference between groups in T_{max} and TF_{150} measured throughout the HIT program. Post-training, the HIT groups had significantly greater TT_{40} performance and PPO compared to CON (Figures 1-2; $P < 0.05$). G_1 also improved PPO significantly more than G_3 (Figure 2; $P < 0.05$). G_1 and G_2 significantly improved VO_{2peak} compared to CON ($P < 0.05$), and G_2 also improved VO_{2peak} significantly more than G_3 ($P < 0.05$) (Figure 3).

Discussion

The first major finding of the present study was that the use of P_{max} as the interval intensity and 60% of T_{max} as the interval duration in the prescription of HIT programs (G_1 and G_2) provided a successful means for enhancing TT_{40} (+5.1-5.8%), PPO (+4.7-6.2%), and VO_{2peak} (+5.4-8.1%) in already highly trained cyclists. These marked enhancements in TT_{40} and PPO ($P < 0.05$) after four weeks of HIT are similar to those that have been previously reported for TT_{40} (+2.1-4.5%) and PPO (+3.6-4.9%) following different HIT programs over a similar time course (6, 11-13). The enhancement of these parameters may be due to two factors. Firstly, the T_{max} intervals in the present study may have been a more taxing HIT program compared to those previously used in HIT-cycling studies (6, 11-13), in that athletes in the present study were pushed to exhaustion on nearly every HIT session. Secondly, our subjects performed a reassessment after two weeks of HIT, whereby adjustments in HIT program parameters were made for the latter two weeks. This reassessment generally made the final two weeks of HIT more challenging than the former, and may also help to explain the large improvement in VO_{2peak} that occurred using the T_{max} HIT programs (G_1 and G_2). VO_{2peak} has been increased (+7%) following eight weeks of HIT in previously-trained cyclists in the off-season ($VO_{2peak} = 56.8 \pm 6.6 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$) (8), but in highly trained cyclists, VO_{2peak} was unchanged following two to six weeks of HIT (5, 6, 11-13). Our findings of enhanced VO_{2peak} using T_{max} intervals (G_1 and G_2) in cyclists are in agreement with those of Smith et al. (10), who noted significant improvements in VO_{2max} (+4.9%; $P < 0.05$) using a similar HIT program in highly trained runners. Collectively, these findings support the theory that training at VO_{2peak} is effective in fostering additional improvements in VO_{2peak} in already highly trained athletes (2).

The second major finding in the present study was that supramaximal HIT (G_3) allowed for equivalent improvements in TT_{40} performance (+4.4%; $P < 0.05$) compared to the more “aerobic” intervals based on T_{max} (G_1 and G_2). PPO was also modestly enhanced (+3.0%; $P < 0.05$)

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compared to CON (-1.1%). The significant improvements in TT_{40} and PPO following supramaximal HIT supports the work of Stepto et al. (11) who noted similar improvements in TT_{40} (+4%) and PPO (+4%) following the same HIT program used in the present study (G_3). However, the 3% increase in VO_{2peak} in G_3 was not different than CON (+1.0%), confirming that improvements in performance can occur independently of improvements in VO_{2peak} (4). Although our study lacks hard metabolic data to explain this finding, improvements in performance following supramaximal HIT could be due to an enhancement of skeletal muscle buffering capacity (13) caused by metabolic acidosis, and/or a simultaneous enhancement of the aerobic and anaerobic metabolic pathways (7).

The third major finding in the present study was the apparent trend in enhanced performance shown by G_2 versus all other groups. This group displayed the greatest overall improvement in TT_{40} , PPO, and VO_{2peak} (Figures 1-3), and also improved PPO and VO_{2peak} significantly more than G_3 and CON ($P < 0.05$). While the use of recovery based on HR returning to a fraction of its maximum is not a new concept (1), to our knowledge only one study has attempted to investigate the effects of different recovery durations on the improvements in performance (14). This study showed no effect on performance and related variables using different recovery durations between HIT bouts. In accordance, we cannot unequivocally state that optimizing recovery from HIT bouts based on HR returning to a fraction of its maximum is superior to a fixed work:recovery ratio, as improvements in PPO and VO_{2max} in G_2 were not significantly different than G_1 . However, in light of the possibility that performance differences between elite athletes may be so slim as to be statistically difficult to detect, optimization of recovery between HIT bouts is likely to be a critical factor in determining performance improvements.

In conclusion, this study has demonstrated that HIT performed at 60% of T_{max} (G_1 and G_2) is an effective means for enhancing TT_{40} performance, PPO, and VO_{2peak} in highly trained cyclists. Moreover, this study supports the findings of prior research (11), in that repeated supramaximal sprinting can significantly enhance TT_{40} performance. Finally, while optimizing recovery between HIT bouts based on HR returning to 65% of HR_{max} (G_2) did not produce significantly greater performance improvements than G_1 , the small difference may be of practical significance in terms of performance differences between elite cyclists. Further in-depth investigation of the biochemical and physiological adaptations accompanying these respective HIT programs are warranted in order to more clearly explain the observed differences between the groups.

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(TF₁₅₀). TF₁₅₀ power output calculated pre-HIT was used throughout the reassessments despite the fact that PPO may have been altered. Volitional fatigue was defined as an inability to maintain pedaling cadence above 60 rev·min⁻¹.

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STATISTICS: Using the standard deviation from TT₄₀ in previous research (6, 12, 13), it was calculated that 10 subjects per group would be required to obtain an effect size of 0.80. A one-way ANOVA examined differences between the groups prior to the HIT intervention. A 4 x 2 (Group x Time) repeated measures ANOVA compared changes in the dependent measures with training between groups. Dunnett's *Post Hoc* comparisons were used to determine whether the HIT groups improved significantly more than the control group, while Tukey's *Post Hoc* compared differences between HIT groups. All statistics were run on SPSS 10.0 for Windows, and alpha was set at 0.05. All data is expressed as $\bar{x} \pm SD$.

RESULTS: Figures 1-3. The effects of two and four weeks of different high-intensity interval training (HIT) programs (G₁, G₂, G₃; see text for details) compared to controls (CON) on 40-km time trial (TT₄₀) performance (Figure 1), peak power output (PPO) (Figure 2), and peak oxygen uptake (VO_{2peak}) (Figure 3).

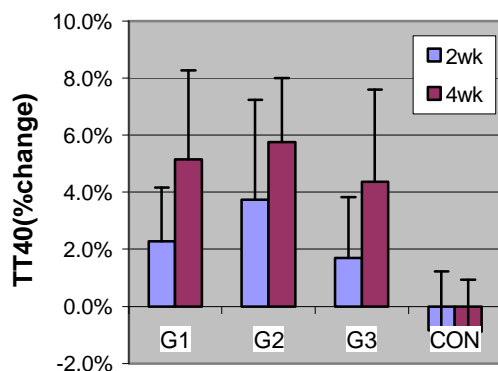


Figure 1. G₁, G₂, and G₃ improved significantly more than controls (CON) (P < 0.05).

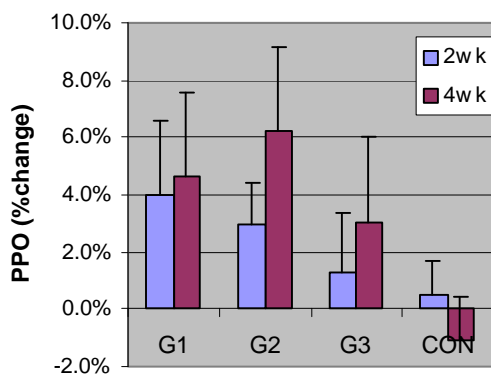


Figure 2. G₁, G₂, and G₃ improved significantly more than controls (CON) (P<0.05), while G₂ improved significantly more than G₃ (P<0.05)

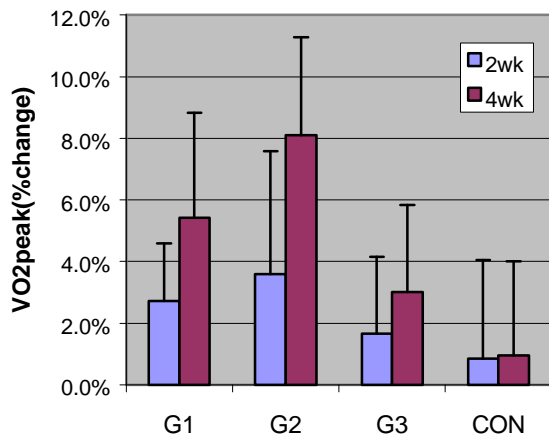


Figure 3. G₁ and G₂ improved significantly more than CON ($P < 0.05$), while G₂ improved significantly more than G₃ ($P < 0.05$).

The coefficient of variation (CV) calculated from the preliminary tests on the dependant measures of TT₄₀, VO_{2peak}, PPO, TF₁₅₀, and T_{max} were found to be 0.9%, 1.8%, 2.1%, 8.2% and 11.9%, respectively. There were no statistical differences between any of the groups on the dependant measures prior to the HIT intervention. There was no significant difference between groups in T_{max}, and TF₁₅₀ measured throughout the HIT program. Post-training, the HIT groups had significantly greater TT₄₀ performance and PPO compared to CON (Figures 1-2; $P < 0.05$). G₁ also improved PPO significantly more than G₃ (Figure 2; $P < 0.05$). G₁ and G₂ significantly improved VO_{2peak} compared to CON ($P < 0.05$), and G₂ also improved VO_{2peak} significantly more than G₃ ($P < 0.05$) (Figure 3).

DISCUSSION: The first major finding of the present study was that the use of P_{max} as the interval intensity and 60% of T_{max} as the interval duration in the prescription of HIT programs (G₁ and G₂) provided a successful means for enhancing TT₄₀ (+5.1-5.8%), PPO (+4.7-6.2%), and VO_{2peak} (+5.4-8.1%) in already highly trained cyclists. These marked enhancements in TT₄₀ and PPO ($P < 0.05$) after four weeks of HIT are similar to those that have been previously reported for TT₄₀ (+2.1-4.5%) and PPO (+3.6-4.9%) following different HIT programs over a similar time course (6, 11-13). The enhancement of these parameters may be due to two factors. Firstly, the T_{max} intervals in the present study may have been a more taxing HIT program compared to those previously used in HIT-cycling studies (6, 11-13), in that athletes in the present study were pushed to exhaustion on nearly every HIT session. Secondly, our subjects performed a reassessment after two weeks of HIT, whereby adjustments in HIT program parameters were made for the latter two weeks. This reassessment generally made the final two weeks of HIT more challenging than the former, and may also help to explain the large improvement in VO_{2peak} that occurred using the T_{max} HIT programs (G₁ and G₂). VO_{2peak} has been increased (+7%) following eight weeks of HIT in previously-trained cyclists in the off-season (VO_{2peak} = 56.8 ± 6.6 ml·kg⁻¹·min⁻¹) (8), but in highly trained cyclists, VO_{2peak} was unchanged following two to six weeks of HIT (5, 6, 11-13). Our findings of enhanced VO_{2peak} using T_{max} intervals (G₁ and G₂) in cyclists are in agreement with those of Smith et al. (10), who noted significant improvements in VO_{2max} (+4.9%; $P < 0.05$) using a similar HIT program in highly trained runners. Collectively, these findings support the theory that training at VO_{2peak} is effective in fostering additional improvements in VO_{2peak} in already highly trained athletes (2).

The second major finding in the present study was that supramaximal HIT (G₃) allowed for equivalent improvements in TT₄₀ performance (+4.4%; $P < 0.05$) compared to the more "aerobic" intervals based on T_{max} (G₁ and G₂). PPO was also modestly enhanced (+3.0%; $P < 0.05$) compared to CON (-1.1%). The significant improvements in TT₄₀ and PPO following supramaximal HIT supports the work of Stepto et al. (11) who noted similar improvements in TT₄₀ (+4%) and PPO (+4%) following the same HIT program used in the present study (G₃). However, the 3% increase in VO_{2peak} in G₃ was not different than CON (+1.0%), confirming that improvements in performance can occur independently of improvements in VO_{2peak} (4). Although our study lacks hard metabolic data to explain this finding, improvements in performance following supramaximal HIT could be due to an enhancement of skeletal muscle buffering capacity (13) caused by metabolic acidosis, and/or a simultaneous enhancement of the aerobic and anaerobic metabolic pathways (7).

The third major finding in the present study was the apparent trend in enhanced performance shown by G₂ versus all other groups. This group displayed the greatest overall improvement in TT₄₀, PPO, and VO_{2peak} (Figures 1-3), and also improved PPO and VO_{2peak} significantly more than G₃ and CON ($P < 0.05$). While the use of recovery based on HR returning to a fraction of its maximum is not a new concept (1), to our knowledge only one study has attempted to investigate the effects of different recovery durations on the improvements in performance (14). This study showed no effect on performance and related variables using different recovery durations between HIT bouts. In accordance, we cannot unequivocally state that optimizing recovery from HIT bouts based on HR returning to a fraction of its maximum is superior to a fixed work:recovery ratio, as improvements in PPO and VO_{2max} in G₂ were not significantly different than G₁. However,

in light of the possibility that performance differences between elite athletes may be so slim as to be statistically difficult to detect, optimization of recovery between HIT bouts is likely to be a critical factor in determining performance improvements.

In conclusion, this study has demonstrated that HIT performed at 60% of T_{max} (G_1 and G_2) is an effective means for enhancing TT_{40} performance, PPO, and VO_{2peak} in highly trained cyclists. Moreover, this study supports the findings of prior research (11), in that repeated supramaximal sprinting can significantly enhance TT_{40} performance. Finally, while optimizing recovery between HIT bouts based on HR returning to 65% of HR_{max} (G_2) did not produce significantly greater performance improvements than G_1 , the small difference may be of practical significance in terms of performance differences between elite cyclists. Further in-depth investigation of the biochemical and physiological adaptations accompanying these respective HIT programs are warranted in order to more clearly explain the observed differences between the groups.

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