Interval training program optimization in highly trained endurance cyclists

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ABSTRACT

LAURSEN, P. B., C. M. SHING, J. M. PEAKE, J. S. COOMBES, and D. G. JENKINS. Interval training program optimization in highly trained endurance cyclists. *Med. Sci. Sports Exerc.*, Vol. 34, No. 11, pp. 1801–1807, 2002. **Purpose:** The purpose of this study was to examine the influence of three different high-intensity interval training (HIT) regimens on endurance performance in highly trained endurance athletes. **Methods:** Before, and after 2 and 4 wk of training, 38 cyclists and triathletes (mean ± SD; age = 25 ± 6 yr; mass = 75 ± 7 kg; $\dot{V}O_{2peak}$ = 64.5 ± 5.2 mL·kg^{-1}·min^{-1}) performed: 1) a progressive cycle test to measure peak oxygen consumption ($\dot{V}O_{2peak}$) and peak aerobic power output (PPO), 2) a time to exhaustion test (T_{max}) at their $\dot{V}O_{2peak}$ power output (P_{max}), as well as 3) a 40-km time-trial (TT_{40}). Subjects were matched and assigned to one of four training groups (G_1, $N = 8$, 8 × 60% T_{max} at P_{max}, 1:2 work:recovery ratio; G_2, $N = 9$, 8 × 60% T_{max} at P_{max}, recovery at 65% HR_{max}; G_3, $N = 10$, 12 × 30 s at 175% PPO, 4.5-min recovery; G_{CON}, $N = 11$). In addition to G_1, G_2, and G_3 performing HIT twice per week, all athletes maintained their regular low-intensity training throughout the experimental period. **Results:** All HIT groups improved TT_{40} performance (+4.4 to +5.8%) and PPO (+3.0 to +6.2%) significantly more than G_{CON} (−0.9 to +1.1%; $P < 0.05$). Furthermore, G_1 (+5.4%) and G_2 (+8.1%) improved their $\dot{V}O_{2peak}$ significantly more than G_{CON} (+1.0%; $P < 0.05$). **Conclusion:** The present study has shown that when HIT incorporates P_{max} as the interval intensity and 60% of T_{max} as the interval duration, already highly trained cyclists can significantly improve their 40-km time trial performance. Moreover, the present data confirm prior research, in that repeated supramaximal HIT can significantly improve 40-km time trial performance. **Key Words:** CYCLIST, ENDURANCE PERFORMANCE, OXYGEN UPTAKE, SHORT-TERM TRAINING

Coaches of endurance athletes have long recognized that high-intensity interval training (HIT) can enhance endurance performance (for recent review, see Laursen and Jenkins (16)). However, little is known of the optimal type of HIT program (i.e., optimal intensity, duration, and recovery) for producing the greatest improvement in endurance performance in those who are already highly trained (16). Some research that has examined HIT program optimization in highly trained runners has used the minimal running speed that elicits $\dot{V}O_{2peak}$ during an incremental test (V_{max}) as the training intensity; specific fractions (50–70%) of the time to exhaustion at V_{max} (T_{max}) have then been used for the interval duration (5,6,23). However, the applicability of this approach to cyclists is yet to be reported.

Only one study has examined HIT program optimization in endurance-trained cyclists (24). The effects of five different HIT programs performed twice per week for three consecutive weeks on endurance performance 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. Whereas one of these programs involved submaximal intervals (8 × 4 min at 85% PPO, 90-s recovery), the other required subjects to perform supramaximal exercise bouts (12 × 30 s at 175% PPO, 4.5-min recovery); endurance performance improved equally in response to both training programs. The finding that repeated supramaximal training could improve endurance performance is intriguing, as supramaximal training has not traditionally been used for endurance events lasting ~1 h. However, the sample size in the study was small ($N = 4$ per group), and the authors noted that the response to training was variable (24).

Little attention has been given to optimizing the recovery duration between HIT work bouts. Generally, fixed work-recovery ratios (i.e., 2:1, 1:1, 1:2) (5,23,25) or recovery durations based on heart rate returning to a fixed percentage of its maximum have been used (1,22). To our knowledge, only one study has examined the influence of different recovery durations between work bouts in highly trained athletes (29); this study showed no effect on performance and related variables in middle-distance runners. Again, however, the sample size in this study was small ($N = 4$ per group). Thus, optimal recovery duration between HIT bouts is yet to be fully described. The purpose of the present study, therefore, was to compare the effects of three different HIT

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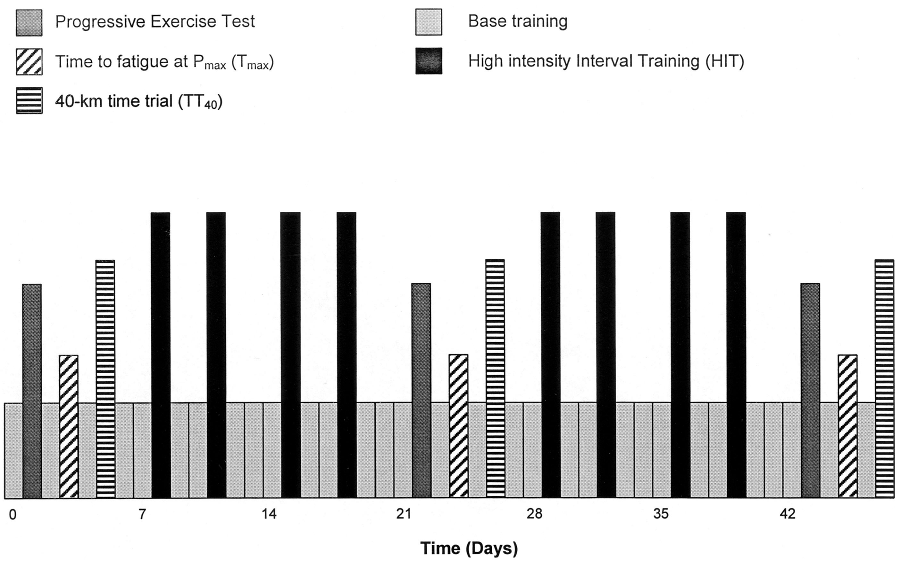

FIGURE 1—Overview of the laboratory testing and training throughout the 7-wk experimental period.

protocols on changes in endurance performance with highly trained cyclists.

METHODS

Subjects. Forty-one highly trained male athletes (mean ± SD; age = 25 ± 6 yr; height = 180 ± 5 cm; mass = 75 ± 7 kg; sum of five skinfolds = 42 ± 15 mm; $\dot{V}O_{2peak}$ = 64.5 ± 5.2 mL·kg^{-1}·min^{-1}) with a minimum of 3 yr cycle training experience volunteered for the present study; subjects included 26 cyclists [14 grade A (top grade), 8 grade B (mid grade), 4 grade C (lower grade)] and 15 multi-sport athletes (12 triathletes, 3 duathletes). All had been training for, and competing in, cycling events on a regular basis for 6 ± 3 yr; their average cycle training distance during the study was 285 ± 95 km·wk^{-1}, which was similar to their training distance before the study. After being fully informed of the risks and stresses associated with the study, subjects completed a medical history questionnaire and gave their written informed consent to participate. The experimental protocol was approved by the Medical Research Ethics Committee of The University of Queensland.

Preliminary testing. Preliminary testing was conducted during the off-season and precompetitive phase of the athletes' yearly training program. All subjects were asked to keep a detailed training diary during this time. For three consecutive weeks before the intervention, athletes reported to the laboratory three times each week to perform: 1) a progressive exercise test to determine $\dot{V}O_{2peak}$ and PPO, 2) a time to exhaustion (T_{max}) test at the $\dot{V}O_{2peak}$ power output (P_{max}), and 3) a 40-km time trial (TT_{40}) on their own road bicycle mounted to a stationary windtrainer. Athletes reported to the laboratory for testing on alternate days in consecutive order, having not trained for at least 12 h; the order of the tests remained the same on each testing occasion (Fig. 1).

Exercise during the first week served to familiarize the subjects, whereas the test results obtained during weeks 2 and 3 were used to establish the coefficients of variation (CV) for baseline measures. Subjects reported to a controlled environmental laboratory condition (~21°C, 40–60%RH, 760–770 mm Hg) at the same time of day for all tests (21). During each test, and on all occasions, incremental power output, speed, and/or exercise time were blinded to the athlete. Athletes were asked to keep their eating habits constant before all tests and to avoid consuming food within 2 h of exercise. Anthropometric data including body mass and sum of five skinfolds (biceps, triceps, subscapular, supraspinale, and abdominal) were measured in duplicate by the same investigator using electronic weighing scales and Harpenden skin-fold calipers (British Indicators, West Sussex, UK).

Progressive exercise test. $\dot{V}O_{2peak}$ was determined using an electronically braked cycle ergometer (Lode Excalibur Sport, Quinton, Seattle, WA) modified with clip-in pedals and low-profile racing handlebars. The saddle and handlebar positions of the cycle ergometer were adjusted to resemble each athlete's own bike, and subjects warmed up at a self-selected pace for 5 min. The incremental test commenced at an initial workload of 100 W; workload thereafter increased by 15 W· 30 s^{-1} until volitional fatigue. Expired air was analyzed for F_EO_2 and F_EC_{O2} every 30 s during exercise (Ametek gas analyzers; SOV S- 3A11 and COV CD3A, Pittsburgh, PA). Minute ventilation ($\dot{V}O_E$) was recorded every 30 s using a turbine ventilometer (Morgan, Model 096, Kent, UK). The gas analyzers were calibrated immediately before and validated after each test using a certified beta gas mixture (Commonwealth Industrial Gas Ltd., Brisbane, Australia); the ventilometer was calibrated before and validated after each test using a 1-L syringe in accordance with the manufacturer's instructions. The metabolic system was verified by the Laboratory Standards Assistance Scheme (9). $\dot{V}O_{2peak}$ was recorded as the highest $\dot{V}O_2$ reading averaged over two consecutive readings, and the PPO was recorded as the highest 30 s power output completed during the incremental test. $\dot{V}O_{2peak}$ was defined by the following criteria: 1) the oxygen consumption ceased to increase linearly with a rising workload and approached

TABLE 1. High-intensity interval training (HIT) programs for groups 1–3 and controls (G_{CON}).

Group	Bouts/ Session	Intensity	Work Duration	Rest Duration
G_1	8	P_{max}	60% T_{max}	120% T_{max}
G_2	8	P_{max}	60% T_{max}	65% HR_{max}
G_3	12	175% PPO	30 s	4.5 min
G_{CON} [control group: Low- to Moderate-Intensity training only]				

P_{max}, minimal power output to elicit $\dot{V}O_{2peak}$; T_{max}, time to exhaustion at P_{max}; PPO, peak power output; HR_{max}, maximal heart rate.

a plateau or dropped slightly, the last two values agreeing within ± 2 mL·kg^{-1}·min^{-1}; 2) 90% of age predicted HR_{peak} was attained; and 3) respiratory exchange ratio (RER) was greater than 1.10.

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 $\dot{V}O_2$ reading that was within 2 mL·kg^{-1}·min^{-1} of the previous reading, despite an increase in workload (3,4). After a 5-min warm-up at 100–250 W, subjects cycled to fatigue at P_{max}; the test was stopped when the cadence fell below 60 rev·min^{-1}. Athletes were blinded to the time elapsed on all testing occasions. The total amount of work completed during the T_{max} test (W_{Tmax}) was calculated as a product of P_{max} and T_{max}.

Laboratory simulated 40-km time trial (TT_{40}). A laboratory-simulated TT_{40} was completed on the athlete's own road bicycle mounted to a stationary windtrainer (Cyclosimulator CS-1000; Cateye Co. Ltd., Osaka, Japan) according to methods that have previously been described (20). The rear tire was inflated to 120 pounds per square inch and placed gently against the friction device before securing; the spring-loaded release brake was removed, placing a wind-regulated friction load against the rear wheel. The athletes same rear wheel was used for each TT_{40}. Total time to complete 40 km was recorded for the calculation of average speed. Subjects were permitted to consume water *ad libitum* during the TT_{40}.

High-intensity interval training (HIT) protocols. Previously, randomizing subjects to training groups produced nonhomogeneity in the training groups that affected the results (unpublished data). To avoid this from occurring, athletes were assigned and matched to groups based first on their TT_{40} performance and second on their $\dot{V}O_{2peak}$. Multisport athletes and cyclists were equally distributed throughout the HIT groups. All HIT groups (Table 1) trained twice per week for 4 wk and were reassessed after 2 and 4 wk of HIT (Fig. 1). The HIT program workload was adjusted after the mid-HIT assessment. At each interval training session, cyclists in group 1 (G_1) completed eight intervals at P_{max}, for a duration equal to 60% T_{max}, with a 1:2 recovery ratio (23). Group 2 (G_2) performed the same work intervals as G_1, except that recovery time was based on HR returning to 65% HR_{max}. Group 3 (G_3) completed twelve 30-s bouts per session at 175% of PPO, separated by 4.5 min of recovery (24). The control group (G_{CON}) was reassessed at the same times, and subjects in this group were asked to maintain their regular low-intensity base-training program (12). Total work completed during each HIT session (W_{train}) was calculated as a product of the amount of time completed at the assigned power output.

Data analysis. Using the standard deviation (3 min) from TT_{40} in previous research (17) to determine the effect size (12), it was calculated that 10 subjects per group would be required to obtain a statistical power of 0.80. A one-way ANOVA examined differences between the groups before the HIT intervention. A repeated-measures ANOVA was run separately in each specific training group in order to determine whether each specific HIT program had an effect on the dependant measures. As well, a 4 × 3 (Group × Time) repeated-measures ANOVA compared the change in the dependent measures over time between the groups; trend analysis delineated the pattern of this change (14). Dunnett's *post hoc* comparisons were used to determine whether the HIT groups improved significantly more than the control group (14), whereas Tukey's *post hoc* compared differences between HIT groups. Pearson product moment examined relationships between variables. All statistics were run on SPSS 10.0 for Windows, and alpha was set at 0.05. All data throughout are expressed as mean ± SD, with the exception of figures, where data are presented as standard errors of the mean for clarity.

RESULTS

Data from two athletes from G_1, and one athlete from G_2 were eliminated from the data analysis due to illness or failure to comply with the training regime. Therefore, eight athletes remained in G_1, nine athletes in G_2, 10 athletes in

TABLE 2. Descriptive characteristics; age, cycle competition experience (exp), height (Ht), weight (Wt), sum of five skinfolds (SSF), peak oxygen consumption ($\dot{V}O_{2peak}$), peak power output (PPO), peak heart rate (HR_{peak}), time to exhaustion (T_{max}) at the minimal power that elicited $\dot{V}O_{2peak}$ during the progressive exercise test (P_{max}), and 40-km time trial performance (TT_{40}); there were no significant differences in any of the pretraining variables between the groups.

	G_1	G_2	G_3	G_{CON}
Age (yr)	26 ± 6	24 ± 7	25 ± 6	25 ± 5
Exp (yr)	7 ± 6	5 ± 4	6 ± 5	5 ± 3
Ht (cm)	181 ± 4	183 ± 7	179 ± 5	178 ± 6
Wt (kg)	76 ± 10	75 ± 4	77 ± 6	73 ± 8
SSF (mm)	44 ± 20	42 ± 10	47 ± 20	36 ± 6
$\dot{V}O_{2peak}$ (mL·kg^{-1}·min^{-1})	66.5 ± 6.2	63.7 ± 4.1	62.6 ± 4.1	65.2 ± 5.9
PPO (W)	439 ± 29	431 ± 23	425 ± 32	422 ± 29
HR_{peak}	194 ± 14	194 ± 14	193 ± 7	189 ± 8
T_{max} (s)	241 ± 37	249 ± 58	251 ± 54	235 ± 35
P_{max} (W)	424 ± 30	413 ± 16	402 ± 35	404 ± 34
TT_{40} (min:s)	57:00 ± 3:08	58:10 ± 3:24	57:29 ± 3:49	57:28 ± 1:54

Data are mean ± SD.

TABLE 3. The total amount of work completed during the T_{max} test (W_{Tmax}) for G_1, G_2, G_3, and G_{CON} throughout the 4-wk high-intensity interval training program.

W_{Tmax} (kJ)	PRE	MID	POST
G_1	121 ± 22	124 ± 23	134 ± 22*
G_2	120 ± 26	119 ± 16	122 ± 22
G_3	120 ± 30	130 ± 44	109 ± 27
G_{CON}	111 ± 19	109 ± 22	103 ± 23

* $P < 0.05$ vs PRE measure.

TABLE 4. Peak oxygen uptake ($\dot{V}O_{2peak}$) scores for G_1, G_2, G_3, and G_{CON} measured throughout the 4-wk high-intensity interval training program.

$\dot{V}O_{2peak}$ ($L \cdot min^{-1}$)	PRE	MID	POST
G_1	5.00 ± 0.52	5.14 ± 0.53	5.26 ± 0.47**
G_2	4.89 ± 0.38	5.06 ± 0.29	5.28 ± 0.35**
G_3	4.91 ± 0.37	4.99 ± 0.42	5.06 ± 0.46*
G_{CON}	4.92 ± 0.45	4.96 ± 0.41	4.96 ± 0.41

* $P < 0.05$ vs PRE measure.
** $P < 0.01$ vs PRE measure.

G_3, and 11 athletes in G_{CON} for the final analysis. Descriptive measures of the training groups before the HIT intervention are presented in Table 2. There were no statistical differences between any of the groups on the dependent measures before the HIT intervention. The CV calculated from the preliminary tests on the dependent measures of TT_{40}, PPO, $\dot{V}O_{2peak}$, and T_{max} were found to be 0.9%, 1.8%, 2.1%, and 6.0%, respectively.

HIT training sessions. W_{train} significantly increased from HIT session number one to eight (linear trend; $P < 0.05$). However, all training groups appeared to improve W_{train} at the same rate (nonsignificant group × time interaction). G_1 and G_2 completed significantly more work than G_3 (both $P < 0.001$), whereas G_1 also performed significantly more W_{train} than G_2 ($P = 0.05$). The mean number of entirely finished prescribed interval bouts completed throughout the HIT sessions were 5 ± 2, 4 ± 3, and 9 ± 3 for G_1, G_2, and G_3, respectively. G_1 had a significantly greater total mean recovery time between bouts (2028 ± 312 s) compared with G_2 (1248 ± 92 s; $P < 0.001$). Mean recovery time between interval bouts for G_2 (based on HR returning to 65% HR_{max}) significantly increased throughout the HIT sessions (117 ± 34 s after bout 1 to 227 ± 105 s after bout 8; $P < 0.05$).

P_{max}, T_{max}, and W_{Tmax}. P_{max} and T_{max} did not significantly change throughout the HIT program. However, W_{Tmax} was significantly different between the groups (i.e., significant interaction; $P < 0.05$). W_{Tmax} was significantly increased post-HIT for G_1, when compared with G_{CON} (Table 3). Although trends for greater increases in W_{Tmax} were present for G_2 ($P = 0.174$) and G_3 ($P = 0.207$), these were not significantly different from G_{CON} (Table 3). The calculated P_{max} of all the athletes was significantly less than their PPO (414 ± 32 W vs 436 ± 31W; $P < 0.01$).

$\dot{V}O_{2peak}$, PPO, and TT_{40} performance. The change in $\dot{V}O_{2peak}$ was significantly different between the groups (i.e., significant interaction; $P < 0.05$). $\dot{V}O_{2peak}$ was significantly increased in G_1, G_2 (both $P < 0.01$), and G_3 ($P < 0.05$) but not in G_{CON} (Table 4). The improvement in $\dot{V}O_{2peak}$ was significantly greater in G_1 and G_2 compared with G_{CON} ($P < 0.05$; Fig. 2). As well, the improvement in $\dot{V}O_{2peak}$ in G_2 was also significantly greater than in G_3 ($P < 0.05$; Fig. 2). PPO and TT_{40} were both significantly enhanced in G_1, G_2 (both $P < 0.01$), and G_3 ($P < 0.05$) but not in G_{CON} (Table 5 and 6). The improvement in TT_{40} performance and PPO in all three HIT groups was significantly greater than in G_{CON} (Figs. 3 and 4; $P < 0.05$). The improvement in PPO in G_2 was also significantly greater than that of G_3 (Fig. 3; $P < 0.05$).

DISCUSSION

The present study has shown that of the three different types of HIT protocols employed, the use of P_{max} as the interval intensity, and 60% of T_{max} as the interval duration elicited the most consistent improvements in endurance performance in already highly trained cyclists. The improvements in TT_{40} (+5.1–5.8%), PPO (+4.7–6.2%), and $\dot{V}O_{2peak}$ (+5.4–8.1%) (Figs. 2–4; all $P < 0.05$) observed for G_1 and G_2 were slightly greater than those previously reported for TT_{40} (+2.1–4.5%) and PPO (+2–4%) after different HIT programs over a similar time course (17,24,27,28). There may be two reasons for this. First, our

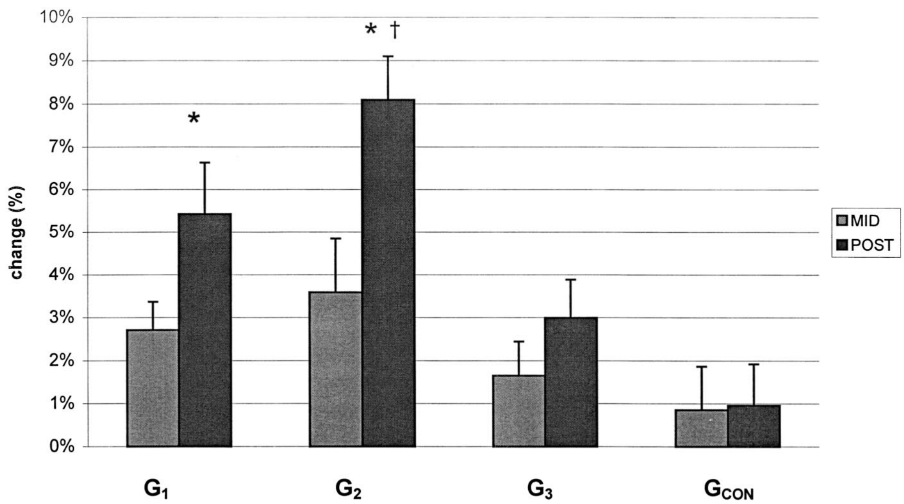

FIGURE 2—Change in peak oxygen uptake ($\dot{V}O_{2peak}$) scores for G_1, G_2, G_3, and G_{CON} measured throughout the 4-wk high-intensity interval training program. * $P < 0.05$ vs G_{CON}; † $P < 0.05$ vs G_3.

TABLE 5. Peak power output (PPO) measured during the progressive exercise test for G_1, G_2, G_3, and G_{CON} (see text for training program details) throughout the high-intensity interval training program.

PPO (W)	PRE	MID	POST
G_1	439 ± 29	456 ± 32	460 ± 37**
G_2	431 ± 32	443 ± 22	457 ± 26**
G_3	425 ± 32	431 ± 32	438 ± 36*
G_{CON}	422 ± 29	425 ± 31	418 ± 28

* $P < 0.05$ vs PRE measure.
** $P < 0.01$ vs PRE measure.

TABLE 6. Average speed during the 40-km time trial (TT_{40}) performance for G_1, G_2, G_3, and G_{CON} throughout the 4-wk high-intensity interval training program.

TT_{40} Speed ($km \cdot h^{-1}$)	PRE	MID	POST
G_1	42.2 ± 2.4	43.2 ± 2.3	44.4 ± 2.8**
G_2	41.4 ± 2.5	42.9 ± 2.1	43.7 ± 2.4**
G_3	41.9 ± 2.6	42.6 ± 2.7	43.7 ± 2.1*
G_{CON}	41.8 ± 1.4	41.4 ± 1.3	41.4 ± 1.5

* $P < 0.05$ vs PRE measure.
** $P < 0.01$ vs PRE measure.

T_{max} intervals may have been more taxing than those previously used in HIT-cycling studies (17,24,27,28). The present subjects were pushed to exhaustion in nearly every HIT session. Indeed, only 64% of the prescribed number of HIT bouts could be completed. Second, the present subjects performed a mid-HIT assessment, and adjustments in HIT program parameters after 2 wk of HIT training resulted in an increase in the training stimulus. This may also help to explain the large improvement in $\dot{V}O_{2peak}$ (Fig. 3; $P < 0.05$) observed for G_1 and G_2. $\dot{V}O_{2peak}$ after HIT in highly trained cyclists has remained either unchanged (15) or has not been reported (17,24,27,28), although it has been increased (+7%) after 8 wk of HIT in previously trained, but not highly trained, cyclists ($\dot{V}O_{2peak}$ = 56.8 ± 6.6 $mL \cdot kg^{-1} \cdot min^{-1}$) (19). Our findings that $\dot{V}O_{2peak}$ improved using T_{max} intervals for G_1 and G_2 are in agreement with those of Smith et al. (23), who noted significant improvements in $\dot{V}O_{2peak}$ (+ 4.9%; $P < 0.05$) using a similar HIT program in highly trained runners. Collectively, these findings support the view (2,3,23) that training at $\dot{V}O_{2peak}$ may be the most effective means of eliciting additional improvements in $\dot{V}O_{2peak}$ in already highly trained athletes.

A second finding in the present study was that improvements in TT_{40} performance (+4.4%; $P < 0.05$; Fig. 4) was similar in response to the supramaximal HIT program. PPO and $\dot{V}O_{2peak}$ were also modestly increased (+3.0%; Figs. 2 and 3; $P < 0.05$). The significant improvements in TT_{40} and PPO after supramaximal HIT are consistent with the findings of Stepto et al. (24), who noted similar improvements in TT_{40} (+4%) and PPO (+4%) after the same HIT program as that used in the present study (Table 1). However, the 3.0% increase in $\dot{V}O_{2peak}$ in G_3 ($P < 0.05$) was not significantly different to that for G_{CON} (+1.0%). Improvements in endurance performance have been shown previously to occur independently of improvements in $\dot{V}O_{2peak}$ (7,8). It is possible that improvements in performance after supramaximal HIT could be due to a simultaneous enhancement of both aerobic and anaerobic metabolic pathways (11,18,26) and/or an increase in skeletal muscle buffering capacity (28) in response to the metabolic acidosis resulting from the repeated supramaximal exercise (10). However, it is also possible that our study lacked the statistical power to demonstrate a significant difference in $\dot{V}O_{2peak}$ between G_3 and G_{CON}.

It is not possible to unequivocally state that one HIT group improved to a greater extent than the other HIT groups. However, there are some nonstatistical trends in our data that should be mentioned. In terms of absolute percent change, G_2 did achieve the greatest improvement in TT_{40}, PPO, and $\dot{V}O_{2peak}$ (Figs. 2–4), and also improved PPO and $\dot{V}O_{2peak}$ significantly more than G_3 and G_{CON} ($P < 0.05$). Although HIT programs have previously used the fractional utilization of HR_{max} as a basis for determining recovery between work bouts (1,22), only one previous study has attempted to investigate the effects of different recovery durations between HIT bouts on the improvements in performance (29), and this study showed no effect on performance and related variables in middle distance runners. It is therefore not possible to unequivocally state that optimizing recovery from HIT bouts based on HR returning to a fraction of its maximum is a more suitable approach to using a fixed work:recovery ratio, as improvements in PPO and $\dot{V}O_{2peak}$ in G_2 were not significantly different to those for G_1. However, given that performances of elite athletes are

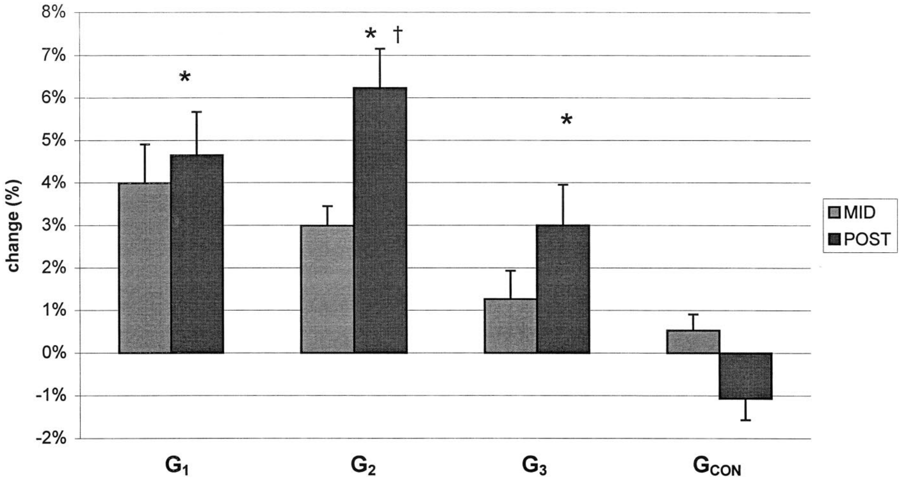

FIGURE 3—Change in peak power output (PPO) measured during the progressive exercise test for G_1, G_2, G_3, and G_{CON} (see text for training program details) throughout the high-intensity interval training program. * $P < 0.05$ vs G_{CON}; † = $P < 0.05$ vs G_3.

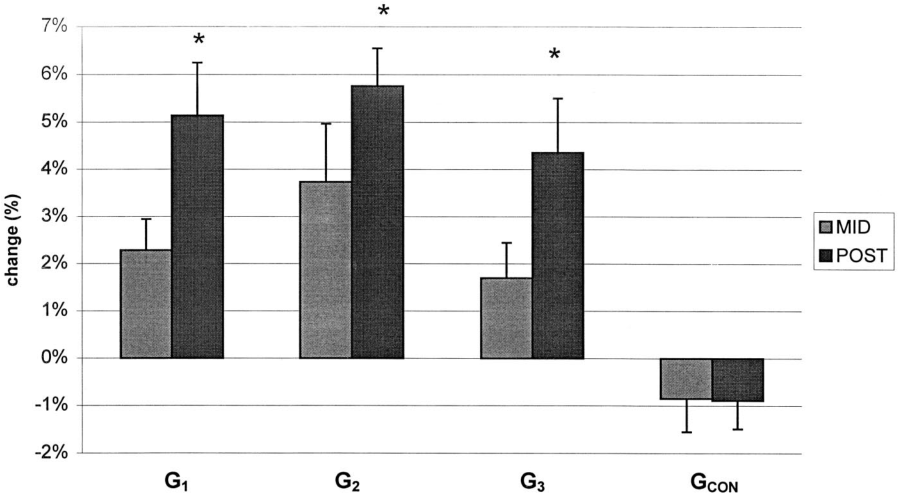

FIGURE 4—Change in average speed during the 40-km time trial (TT_{40}) for G_1, G_2, G_3, and G_{CON} throughout the 4-wk high-intensity interval training program. * $P < 0.05$ vs G_{CON}.

separated by very small margins that would be difficult to statistically detect (12,13), the apparent trend toward the improvement in performance after recovery optimization between HIT bouts may be important in practical terms.

In conclusion, this study has shown that HIT performed at intensities of P_{max} and durations of 60% of T_{max} (G_1 and G_2) is an effective means for enhancing 40-km time trial performance, peak power output, and $\dot{V}O_{2peak}$ in highly trained cyclists. Moreover, the present research has confirmed that repeated supramaximal training can significantly enhance both peak power output, $\dot{V}O_{2peak}$, and 40-km time trial performance.

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REFERENCES

1. Acevedo, E. O., and A. H. Goldfarb. Increased training intensity effects on plasma lactate, ventilatory threshold, and endurance. *Med. Sci. Sports Exerc.* 21:563–568, 1989.
2. Billat, L. V. Interval training for performance: a scientific and empirical practice. Part I: aerobic interval training. *Sports Med.* 31:13–31, 2001.
3. Billat, L. V., and J. P. Koralsztein. Significance of the velocity at VO_{2max} and time to exhaustion at this velocity. *Sports Med.* 22:90–108, 1996.
4. Billat, V., M. Faina, F. Sardella, et al. A comparison of time to exhaustion at VO_{2max} in elite cyclists, kayak paddlers, swimmers and runners. *Ergonomics* 39:267–277, 1996.
5. Billat, V. L., B. Flechet, B. Petit, G. Muriaux, and J. P. Koralsztein. Interval training at $\dot{V}O_{2max}$: effects on aerobic performance and overtraining markers. *Med. Sci. Sports Exerc.* 31: 156–163, 1999.
6. Billat, V. L., J. Slawinski, V. Bocquet, et al. Intermittent runs at the velocity associated with maximal oxygen uptake enables subjects to remain at maximal oxygen uptake for a longer time than intense but submaximal runs. *Eur. J. Appl. Physiol.* 81:188–196, 2000.
7. Davies, K. J., C. M. Donovan, C. J. Refino, G. A. Brooks, L. Packer, and P. R. Dallman. Distinguishing effects of anemia and muscle iron deficiency on exercise bioenergetics in the rat. *Am. J. Physiol.* 246:E535–E543, 1984.
8. Davies, K. J., J. J. Maguire, G. A. Brooks, P. R. Dallman, and L. Packer. Muscle mitochondrial bioenergetics, oxygen supply, and work capacity during dietary iron deficiency and repletion. *Am. J. Physiol.* 242:E418–427, 1982.
9. Gore, C. J., P. G. Catcheside, S. N. French, J. M. Bennett, and J. Laforgia. Automated $\dot{V}O_{2max}$ calibrator for open-circuit indirect calorimetry systems. *Med. Sci. Sports Exerc.* 29:1095–1103, 1997.
10. Hargreaves, M., M. J. Mckenna, D. G. Jenkins, et al. Muscle metabolites and performance during high-intensity, intermittent exercise. *J. Appl. Physiol.* 84:1687–1691, 1998.
11. Harmer, A. R., M. J. Mckenna, J. R. Sutton, et al. Skeletal muscle metabolic and ionic adaptations during intense exercise following sprint training in humans. *J. Appl. Physiol.* 89:1793–1803, 2000.
12. Hopkins, W. G. Measures of reliability in sports medicine and science. *Sports Med.* 30:1–15, 2000.
13. Hopkins, W. G., and D. J. Hewson. Variability of competitive performance of distance runners. *Med. Sci. Sports Exerc.* 33: 1588–1592, 2001.
14. Howell, D. C. *Statistical Methods for Psychology*, 4th Ed. Belmont, CA: Duxbury Press, 1997, pp. 380–396.
15. Laursen, P. B., M. A. Blanchard, and D. G. Jenkins. Acute high-intensity interval training improves T_{vent} and peak power output in highly-trained males. *Can. J. Appl. Physiol.* 27:336–348, 2002.
16. Laursen, P. B., and D. G. Jenkins. The scientific basis for high-intensity interval training: optimising training programmes and maximising performance in highly trained endurance athletes. *Sports Med.* 32:53–73, 2002.
17. Lindsay, F. H., J. A. Hawley, K. H. Myburgh, H. H. Schomer, T. D. Noakes, and S. C. Dennis. Improved athletic performance in highly trained cyclists after interval training. *Med. Sci. Sports Exerc.* 28:1427–1434, 1996.
18. Macdougall, J. D., A. L. Hicks, J. R. Macdonald, R. S. Mckelvie, H. J. Green, and K. M. Smith. Muscle performance and enzymatic adaptations to sprint interval training. *J. Appl. Physiol.* 84:2138–2142, 1998.
19. Norris, S. R., and S. R. Petersen. Effects of endurance training on transient oxygen uptake responses in cyclists. *J. Sports Sci.* 16: 733–738, 1998.
20. Palmer, G. S., S. C. Dennis, T. D. Noakes, and J. A. Hawley. Assessment of the reproducibility of performance testing on an air-braked cycle ergometer. *Int. J. Sports Med.* 17:293–298, 1996.
21. Reilly, T., and C. Baxter. Influence of time of day on reactions to cycling at a fixed high intensity. *Br. J. Sports Med.* 17:128–130., 1983.

22. Simoneau, J. A., G. Lortie, M. R. Boulay, M. Marcotte, M. C. Thibault, and C. Bouchard. Effects of two high-intensity intermittent training programs interspaced by detraining on human skeletal muscle and performance. *Eur. J. Appl. Physiol.* 56:516–521, 1987.
23. Smith, T. P., L. R. Mcnaughton, and K. J. Marshall. Effects of 4-wk training using V_{max}/T_{max} on $\dot{V}O_{2max}$ and performance in athletes. *Med. Sci. Sports Exerc.* 31:892–896, 1999.
24. Stepto, N. K., J. A. Hawley, S. C. Dennis, and W. G. Hopkins. Effects of different interval-training programs on cycling time-trial performance. *Med. Sci. Sports Exerc.* 31:736–741, 1998.
25. Stepto, N. K., D. T. Martin, K. E. Fallon, and J. A. Hawley. Metabolic demands of intense aerobic interval training in competitive cyclists. *Med. Sci. Sports Exerc.* 33:303–310, 2001.
26. Tabata, I., K. Nishimura, M. Kouzaki, et al. Effects of moderate-intensity endurance and high-intensity intermittent training on anaerobic capacity and $\dot{V}O_{2max}$. *Med. Sci. Sports Exerc.* 28:1327–1330, 1996.
27. Westgarth-Taylor, C., J. A. Hawley, S. Rickard, K. H. Myburgh, T. D. Noakes, and S. C. Dennis. Metabolic and performance adaptations to interval training in endurance-trained cyclists. *Eur. J. Appl. Physiol.* 75:298–304, 1997.
28. Weston, A. R., K. H. Myburgh, F. H. Lindsay, S. C. Dennis, T. D. Noakes, and J. A. Hawley. Skeletal muscle buffering capacity and endurance performance after high-intensity training by well-trained cyclists. *Eur. J. Appl. Physiol.* 75:7–13, 1997.
29. Zavorsky, G. S., D. L. Montgomery, and D. J. Pearsall. Effect of intense interval workouts on running economy using three recovery durations. *Eur. J. Appl. Physiol.* 77:224–230, 1998.