Four-Second Power Cycling Training Increases Maximal Anaerobic Power, Peak Oxygen Consumption, and Total Blood Volume

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ABSTRACT

SATIROGLU, R., S. LALANDE, S. HONG, M. J. NAGEL, and E. F. COYLE. Four-Second Power Cycling Training Increases Maximal Anaerobic Power, Peak Oxygen Consumption, and Total Blood Volume. *Med. Sci. Sports Exerc.*, Vol. 53, No. 12, pp. 2536–2542, 2021. **Introduction:** High-intensity interval training is an effective tool to improve cardiovascular fitness and maximal anaerobic power. Different methods of high-intensity interval training have been studied but the effects of repeated maximal effort cycling with very short exercise time (i.e., 4 s) and short recovery time (15–30 s) might suit individuals with limited time to exercise. **Purpose:** We examined the effects of training at near maximal anaerobic power during cycling (PC) on maximal anaerobic power, peak oxygen consumption ($\dot{V}O_{2peak}$), and total blood volume in 11 young healthy individuals (age: 21.3 ± 0.5 yr) (six men, five women). **Methods:** Participants trained three times a week for 8 wk performing a PC program consisting of 30 bouts of 4 s at an all-out intensity (i.e., 2 min of exercise per session). The cardiovascular stress progressively increased over the weeks by decreasing the recovery time between sprints (30–24 s to 15 s), and thus, total session time decreased from 17 to <10 min. **Results:** Power cycling elicited a 13.2% increase in $\dot{V}O_{2peak}$ (Pre: 2.86 ± 0.18 L·min^{-1}, Post: 3.24 ± 0.21 L·min^{-1}; P = 0.003) and a 7.6% increase in total blood volume (Pre: 5139 ± 199 mL, Post: 5529 ± 342 mL; P < 0.05). Concurrently, maximal anaerobic power increased by 17.2% (Pre: 860 ± 53 W, Post: 1,009 ± 71 W; P < 0.001). **Conclusions:** A PC training program employing 30 bouts of 4 s duration for a total of 2 min of exercise, resulting in a total session time of less than 10 min in the last weeks, is effective for improving total blood volume, $\dot{V}O_{2peak}$ and maximal anaerobic power in young healthy individuals over 8 wk. These observations require reconsideration of the minimal amount of exercise needed to significantly increase both maximal aerobic and anaerobic power. **Key Words:** CARDIOVASCULAR FITNESS, ENDURANCE, EXERCISE, PERFORMANCE, TIME-EFFICIENT

In 1979, Costill et al. (1) demonstrated that training consisting of 30 s of all-out leg extensions, performed approximately three times per session with four sessions per week for 7 wk, can significantly increase muscle oxidative enzyme activity. Since the new millennium, there has been renewed interest in "high-intensity interval training" (HIIT) with general exercise prescriptions that are quite varied but when initially practiced were between 85% and 170% of $\dot{V}O_{2max}$ (2,3). A more recent addition to the HIIT repertoire is the introduction of "sprint interval training" (SIT), initially studied by Gibala and colleagues (4), and involving six repeated bouts of "all-out" cycling for 30 s, resulting in extreme fatigue with perceived exertions of "very hard" or higher (5). This type of SIT training, requiring 30 min·d^{-1} of total time, results in a modest 7% increase in $\dot{V}O_{2peak}$ and a modest increase in muscle mitochondrial activity, which confirms that it possesses a component of aerobic stimulation (6). In an attempt to reduce the fatigue encountered in all-out 30-s bouts, Metcalfe et al. (7) have introduced 20-s bouts of all-out cycling performed two to three times per session and three times per week. However, reducing cycling bout time to 10 s attenuated the increase in maximal aerobic capacity but had no effect on affective and perceptual responses (8).

The Physical Activity Guidelines for Americans now recommend at least 75 to 150 min·wk^{-1} of vigorous intensity aerobic physical activity or at least 150 to 300 min·wk^{-1} of moderate-intensity aerobic physical activity to improve health and performance (9). Furthermore, the American College of Sports Medicine has recently added the amendment that the exercise does not need to be continuous (10). Compliance to Physical Activity Guidelines are notably low (i.e., 10%–20%),

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and lack of time is identified as one of the main barriers from being physically active (11). High-intensity interval training could be a time-efficient alternative method of training, enabling one to achieve a higher total accumulated high-intensity exercise (e.g., 85%–400% $\dot{V}O_{2max}$; with 400% being a power output that is four times higher than the minimal power needed to reach $\dot{V}O_{2max}$). High-intensity interval training also reduces time in a session compared with continuous training (12,13). We recently reported that hourly bouts of acute 4 s of maximal intensity cycle sprints that interrupt prolonged sitting can significantly lower the next day's postprandial plasma triglyceride response while increasing fat oxidation (14). The present study extends those acute observations of the effects of 4-s maximal intensity bouts to 8 wk of training. Our goal is to determine if exercise training sessions involving only 2 min of total exercise time are effective for raising maximal aerobic and maximal anaerobic power.

Multiple physiological factors determine cardiovascular fitness that is best represented by $\dot{V}O_{2max}$ (15). Total blood volume is one factor as expansion of red blood cell volume (RBCV) can increase over weeks or months of endurance training (16). Training at 90% of $\dot{V}O_{2peak}$ using 2-min work: 2-min recovery bouts has been reported to increase blood volume by 10% after training 3 $d \cdot wk^{-1}$ for 12 wk (17). Another protocol reported that training at 95% to 100% of $\dot{V}O_{2max}$ using 60-s work with 75-s active recovery increased plasma volume by 10.8% after six sessions over a 12-d training period (18). It is unknown if repeated maximal intensity 4-s sprints can improve hematological variables and $\dot{V}O_{2peak}$.

It is our premise that "all-out" exercise should be used as it is the most potent stimulus owing to the maximal number of motor units it recruits when generating maximal anaerobic power that is approximately 4 times higher than the minimal power needed to elicit $\dot{V}O_{2max}$ (i.e., 400% $\dot{V}O_{2max}$). The duration of "all-out" exercise should roughly coincide with the amount of energy stored in chemical energy (ATP-PCr) which is roughly 4 s (19). The 4-s bouts of "all-out" cycling can be made practical using an "Inertial Load Ergometer" for sprint training (13,20). The amount of recovery between sprints should be enough time to sufficiently resynthesize ATP-PCr via oxidative phosphorylation, but not too much time to produce a low cardiovascular stress. We have recently observed that taking 30-s rest between 30 successive "all-out" 4-s cycle sprints elicited a moderate cardiovascular stimulus (i.e., 56% $\dot{V}O_{2max}$) and that 15-s rest elicited 72% $\dot{V}O_{2max.}$ (13). Taking 15 s of recovery between the 30 successive, 4-s sprints represents a total exercise time only of 2 min in a period of less than 10 min.

A short duration of exercise might be more appealing for those with little time. The objective of this study was to evaluate the effects of 8 wk of training at maximal anaerobic power when cycling (i.e., PC) for simultaneously stimulating increases in maximal anaerobic power as well as maximal aerobic power. The role of increased blood volume for increasing $\dot{V}O_{2peak}$ was specifically investigated. Given our observation that 15 s of recovery between sprints elicits 72% $\dot{V}O_{2peak}$ and that repeated sprints can be performed at >80% of maximal anaerobic power (13), it is hypothesized that this short duration of daily training (i.e., 2 $min \cdot d^{-1}$) might simultaneously increase in both maximal aerobic and anaerobic power.

METHODS

Participants

Participants were recruited from the University of Texas at Austin and the Austin area. Eleven (six men, 5 women) young (21.3 ± 0.5 yr), healthy, and recreationally active participants completed the study. Their initial weight was 68.1 ± 12 kg, and they were untrained. Participants were informed about the training program and risks before signing a consent form approved by the institutional review board of the University of Texas at Austin (ClinicalTrials.gov Identifier: NCT04656509).

Study Design

The entire study lasted approximately 10 wk, involving an 8-wk training period with 24 PC sessions. Each participant trained three times per week (e.g., Monday, Wednesday, and Friday) and was instructed to maintain their normal diet and activity programs. Performance tests and hematological measurements took place both before and after the 8 wk of training.

On day 1 of testing, we measured the participant's weight and hematological variables. This was followed by a familiarization session with the PC protocol. Later, participants were timed while sprinting for 20 yards on an indoor hardwood court surface. Afterward, the Wingate anaerobic cycling test was administered (21). On day 2, the countermovement jump (CMJ) test and another familiarization to PC was completed. Lastly, peak oxygen consumption ($\dot{V}O_{2peak}$) was evaluated on an electronically braked cycling ergometer, whereas HR was monitored continuously. Prior to the first PC session on day 3, participants were tested for maximal anaerobic power when cycling (i.e., PC), using the inertial-load ergometer. Maximum was taken as the average of the two highest values from a total of 5 sprints with 2 min of rest between each sprint. After 8 wk of PC, the same order of testing was followed for the posttraining testing.

Test Procedure

Familiarization with equipment and PC protocol. As mentioned, on the initial visit to the laboratory and on day 2, participants were introduced to the PC. In order to overcome the small learning effect for PC, participants performed a total of five sessions on separate non-consecutive days, which involved 5 sprints per session. This program has been shown to produce learning and reproducible results with a change of less than 5% in maximal anaerobic power output (22).

Inertial-load test equipment. A specialized cycle with a flywheel inertial-load (0.91 $kg \cdot m^{-2}$ and gear ratio 3.71, Sports Texas Nutrition Training and Fitness, Inc., Austin, TX) was used for measuring maximal anaerobic power as well as for training. The inertial-load testing protocol involved 4 s of maximal cycling against the inertia of flywheel (without any external load) (20). Power outputs were recorded via monitoring the velocity of the flywheel using an optical encoder disk on the flywheel, an optical sensor (U.S. Digital, Vancouver,

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WA) and a laboratory computer. Power was calculated as the product of inertial-load, velocity and acceleration. Maximal anaerobic power was calculated as the highest value averaged throughout one entire pedal revolution.

Power cycling sprint training (PC). For each 'all-out' bout of cycling, participants were asked to cycle as hard and as fast as possible for 4 s. Participants started from zero RPM and accelerated to approximately 160 RPM, with maximal anaerobic power being reached within 1 to 2 s. The torque was high at the beginning of the bout, however, as the velocity of the flywheel increased, the resistive torque progressively decreased. Thus, training bouts included sections of high torque (0–90 RPM), maximal power (90–130 RPM), and maximal velocity of cycling (~160 RPM). Each portion was performed with high effort to ensure the highest amount of voluntary muscle fiber recruitment throughout the complete range of contraction velocities.

Training sessions consisted of 120 s of actual exercise time with a short warm-up for 5 min at ~50% of $\dot{V}O_{2peak}$ or ~100 W. Given the progressive reductions in recovery time with 8 w of training, total time spent performing the 30 sprints and recovering was ~17 min for week 1 (30-s passive recovery), ~14 $min \cdot wk^{-1}$ 2 to 4 (24-s passive recovery), and ~9.5 min for wk 5 to 8 (15-s passive recovery), not including warm-up. During the training sessions, the ratings of perceived exertion (RPE; Borg scale) were recorded after the 10th, 20th, and 30th bouts of the session. The power for each sprint was immediately reported to the participant.

Performance Tests

20-yard dash test. On day 1, participants performed three maximal 20-yard running sprints with a 2-min recovery period. The fastest running time was recorded using a single-beam timing system (TC Photogate; Brower Timing System, Draper, UT).

Wingate anaerobic test. Participants cycled on a Monark ergometer bike (894E Sprint Bike, Monark, Sweden). The protocol consisted of 30 s all-out sprinting and two prestarts. Prestarts involved 3 to 5 s of accelerations against the mechanically braked cycling flywheel and allowed the participant to become familiar with generating a high pedaling rate after load ($0.09\ kg \cdot kg^{-1}$ body weight) is applied (21).

Countermovement vertical jump test. Participants reached the highest point with their arm to get a "standing reach." Then, participants were asked to jump as high as possible. Countermovement jump height was measured using the Vertec device (Sports Imports, Hilliard, OH) with three to four attempts.

Peak oxygen consumption test. During this test, participants exercised on a laboratory cycle ergometer (Excalibur Sport, Lode, Groningen, The Netherlands) while breathing through a two-way valve (Hans-Rudolph, Shawnee, KS) connected to a mixing chamber. Expired gases and ventilation were analyzed using a calibrated metabolic cart (Models S-3A/I and CD-3A; AEI Technologies, Bastrop, TX). Heart rate was measured continuously from a strap worn around their chest (Wahoo Fitness, Atlanta, GA) as a verification method for obtaining $\dot{V}O_{2peak}$. Testing included 4–2–2–1–1 min stages that aimed to reach predicted $\dot{V}O_{2peak}$. Participants cycled until they could not maintain a cadence above 50 RPM despite strong encouragement.

Hematological variables. Participants' hematological variables were measured using a modified version of the optimized carbon monoxide rebreathing technique (23,24). Participants laid down for 20 min before a venous blood draw was obtained to measure baseline levels of hematocrit, hemoglobin, and carboxyhemoglobin using a blood gas analyzer (ABL 80 FLEX OSM; Radiometer, Copenhagen, Denmark). Participants then rebreathed for 2 min using a low-volume closed circuit system containing an individual dose of carbon monoxide calculated based on body surface area and hemoglobin concentration (25). Another blood draw was obtained 10 min after the start of the rebreathing to determine carboxyhemoglobin levels. Red blood cell volume, plasma volume (PV) and total blood volume, calculated from the change in carboxyhemoglobin levels induced by the carbon monoxide rebreathing (25). Our coefficient of variation for hemoglobin mass, based on duplicate measures performed on consecutive days in five individuals, was 2.6%.

Statistical Analysis

Data are presented as mean ± SEM. $\dot{V}O_{2peak}$, inertial-load cycling maximal anaerobic power, Wingate power, CMJ, 20-yard dash time, RPE, total blood volume, PV, and RBCV were analyzed using a paired t-test. A repeated measures one-way analysis of variance was used to compare the torque and power versus velocity relationship before and after training. Differences in pretraining and posttraining of power and torque were determined by repeated measures two-way ANOVA (Trial–RPM). Data were analyzed using Graph Pad Prism software (GraphPad 8.0) for Windows. The level of statistical significance was set at $P < 0.05$.

RESULTS

Training outcomes. Participants completed 8 wk of training with a total of 93% participation during the scheduled training sessions and all participants completed all sessions through rescheduling. Body mass increased significantly after training (Pre: 68.0 ± 3.8 kg, Post: 70.0 ± 3.9 kg; +2.9%, $P < 0.05$). As the recovery periods decreased over weeks of training, the highest training power outputs did not change (Fig. 1). However, the average power during the training bouts was reduced significantly ($P < 0.05$) during the weeks with 15 s of recovery (week 5–8). RPE when taken after 15 s of rest between bouts increased progressively and significantly after 10, 20 and 30 bouts (RPE; 13.0 ± 0.3 and 14.6 ± 0.3 and 15.8 ± 0.5) ($P < 0.001$) when measured during week 8, but RPE did not become "very hard" (i.e., 17).

Cardiovascular changes. The training resulted in significant increases in total blood volume and RBCV (i.e., 7.5% and 5.0% respectively; $P < 0.05$) (Table 1). Both pretraining and posttraining data of RBCV versus $\dot{V}O_{2peak}$, both expressed

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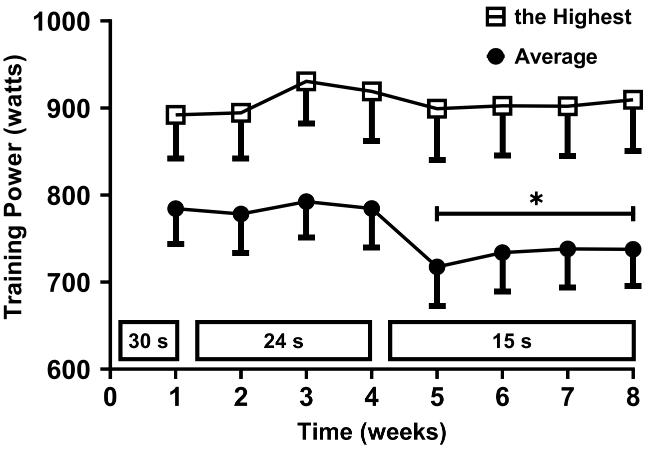

FIGURE 1—Weekly training power expressed as the highest single sprint bout and the average power outputs during the training sessions of 30 repeated sprints. Rest period between bouts progressively decreased from 30 s (week 1), to 24 s (week 2–4), and to 15 s (week 5–8). Average power with the 15-s recovery period during wk 5 to 8 was significantly reduced (*$P < 0.05$) compared with prior weeks. Values are means ± SEM ($n = 11$).

per kilogram of body weight, showed significant correlations (r = 0.72; $P < 0.017$ and $r = 0.80$; $P < 0.005$) and thus approximately one-half of the variance ($r^2 = 0.58$) in $\dot{V}O_{2peak}$ in this population was accounted for by RBCV (Fig. 2).

Aerobic power. After 8 wk of PC, $\dot{V}O_{2peak}$ increased by 13.2% ($P < 0.01$; Table 2). This was accompanied by a significant improvement in the peak aerobic power at $\dot{V}O_{2peak}$ ($P < 0.01$) and in the time to exhaustion during the incremental cycling test ($P < 0.01$; Table 2).

Maximal anaerobic power. Different test methods of maximal anaerobic power were applied to compare the inertial-load ergometer to commonly used methods (e.g., CMJ, Wingate) and to determine the efficacy of sprint cycling on a different exercise mode (i.e., running). Maximal anaerobic power (P_{max}) using the inertial-load ergometer increased (17.2%, $P < 0.001$; Table 3), and Power and torque at all velocities of 50–160 RPM were significantly increased ($P < 0.0001$; Fig. 2). Increases in P_{max} were accompanied by an approximate 15%–20% increase in torque at velocities of 50–130 RPM (Fig. 3). However, at velocities of 140–160 RPM, torque was increased by 30%–40% as a result of training.

Furthermore, CMJ increased 2.5 cm with training ($P < 0.001$) yet the improvement in 20-yard dash time was not statistically significant ($P = 0.12$). The highest power during the Wingate test increased ~10% and the 30-s average power also increased ~10% ($P < 0.001$; Table 3). P_{max} measured on the inertial-load ergometer was found to be 25% higher ($P < 0.01$) than the highest measured maximal anaerobic power with the Wingate test.

TABLE 1. Hematological variables pre and post 8 wk of power cycling training and percent change.

Variables	Pretraining	Posttraining	% Change
Total blood volume (mL)	5139 ± 199	5529 ± 342*	+7.5*
PV (mL)	3059 ± 108	3342 ± 199**	+9.2
RBCV (mL)	2081 ± 138	2187 ± 167*	+5.0*

Values are mean ± SEM ($n = 10$).
*Significantly different from the pretraining ($P < 0.05$).
**Different from the pretraining ($P = 0.07$).

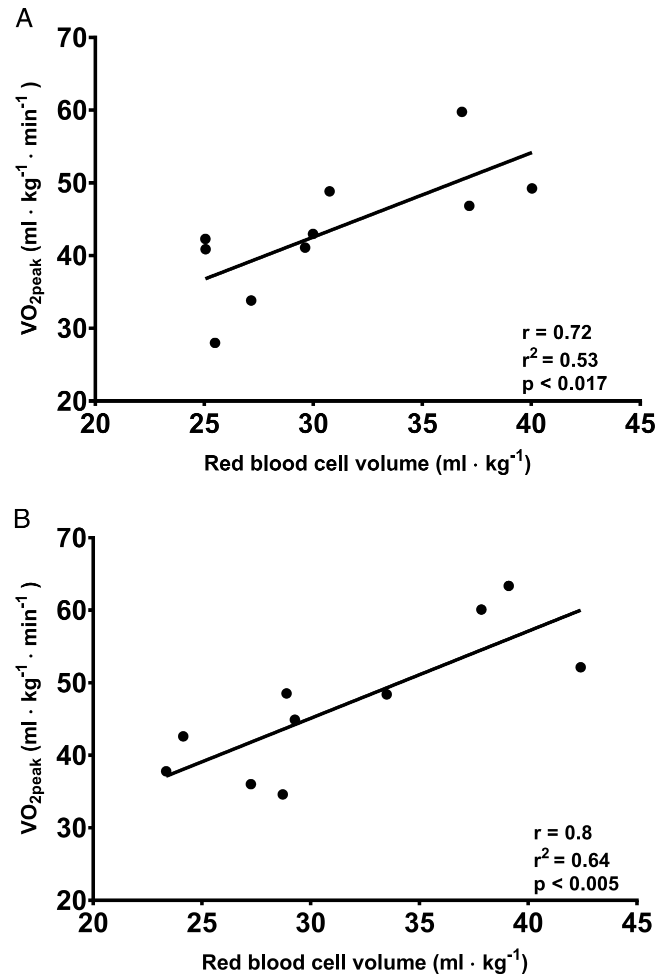

FIGURE 2—Correlation between $\dot{V}O_{2peak}$ and red blood cell volume, expressed per kilogram of body weight using data Pre (A) and Post (B) training response in men and women ($n = 10$).

DISCUSSION

One novel aspect of this study is the use of both very short work (e.g., 4-s eliciting P_{max}) and recovery periods (e.g., 15 to 30 s) for 30 repetitions using an Inertial Load Ergometer for generating maximal power while cycling (i.e., PC). We have described that this protocol (13) elicits a moderately high aerobic stress (56% to 72% $\dot{V}O_{2peak}$) with 30 and 15 s of passive recovery, respectively, which agrees with the present observation

TABLE 2. Maximal aerobic performance responses pre and post 8 wk of power cycling training and percent change.

Variables	Pretraining	Posttraining	% Change
$\dot{V}O_{2peak}$ (L·min^{-1})	2.86 ± 0.18	3.24 ± 0.21*	+13.2*
$\dot{V}O_{2peak}$ (mL·kg^{-1}·min^{-1})	42.7 ± 2.6	47.3 ± 2.7*	+10.8*
Peak aerobic power (W)	209 ± 13	227 ± 14*	+8.9*
Time to exhaustion (s)	563 ± 28	625 ± 17*	+10.9*
Maximal HR (bpm)	187 ± 1	188 ± 1	+0.7
Respiratory exchange ratio	1.16 ± 0.01	1.09 ± 0.01	–4.5

Values are mean ± SEM ($n = 11$).
*Significantly different from the pretraining ($P < 0.01$).

TABLE 3. Maximal anaerobic power responses before and after 8 wk of PC training and percent change.

Variables	Pretraining	Posttraining	% Change
Maximal power—PC (W)	860 ± 53	1009 ± 71*	+17.2*
Maximal power—PC ($W \cdot kg^{-1}$)	12.8 ± 0.7	14.5 ± 0.9**	+13.8**
Wingate maximal power (W)	708 ± 41	777 ± 46***	+9.7***
Wingate 30-s average power (W)	503 ± 29	552 ± 32*	+9.8*
CMJ (cm)	39.9 ± 3.3	42.4 ± 3.2	+6.3*
20-Yard dash (s)	3.16 ± 0.09	3.09 ± 0.09	−2.21

Values are mean ± SEM (n = 11).
Significantly different from the pretraining data point (*P < 0.001; **P = 0.003; ***P < 0.05).

that 8 wk of training elicited a 13.2% increase in $\dot{V}O_{2peak}$. Furthermore, the 30 repeated 4-s sprints stimulated a 17.2% increase in maximal anaerobic power. What is also noteworthy about these findings is that both anaerobic and aerobic adaptations were developed with a protocol involving only 120 s of exercise and taking <10 $min \cdot d^{-1}$ of total time to perform in the final weeks of the training. This PC program appears to be a time efficient method for improving both maximal aerobic power as well as maximal anaerobic power.

It seems obvious that P_{max} was increased due to the neuromuscular specificity of training performed at an average of ~80% of P_{max} and 700 to 800 W (26). In performing these intervals the cardiovascular system was stimulated, as judged by a continuous HR elevation (13). The 4-s bout of maximal exercise has been reported to lower muscle ATP-PCr stores that are subsequently replenished through oxidative metabolism (27). The work rest ratio during the final 4 wk of training (e.g., 4 s/15 s) elicited fatigue as judged by a small drop in average power over the 30 bouts (Fig. 1), yet the 15-s rest provides the stimulus to elevate $\dot{V}O_2$ to a level we previously found to be 72% $\dot{V}O_{2peak}$ (13). It is likely that the last 4 wk of training were the most potent for stimulating cardiovascular adaptations. Therefore, both maximal anaerobic and aerobic power were stimulated during the 4-s sprints and $\dot{V}O_2$ was stimulated during the 15-s recovery so that oxidative phosphorylation can increase ATP-PCr (27). This work rest ratio using "all-out" efforts, which in training elicits 80%–95% of P_{max}, is a delicate balance for achieving both a high level of anaerobic and aerobic stimulation without fatigue at least for a 10 min duration. Buchheit et al. (2) speculated that repeated sprint exercise sessions might elicit an elevated $\dot{V}O_2$ (>75% of $\dot{V}O_{2max}$) similar to the present protocol (i.e., 72% of $\dot{V}O_{2peak}$). They also suggested that in order to increase the %$\dot{V}O_{2max}$ (e.g., over 75% of $\dot{V}O_{2max}$) during the training session, exercise bouts should be at least 4 s in duration with recovery time less than 20 s. This is similar to the 4-s maximal bouts used presently that progressed to taking 15-s rest.

The present 13.2% increase in $\dot{V}O_{2peak}$ over 8 wk occurred in association with a significant 7.5% increase (i.e., 390 mL) in total blood volume and a 5% increase in RBCV (i.e., 106 mL). A 400 mL increase of total blood volume has been shown to acutely raise $\dot{V}O_{2peak}$ by 4% in highly trained endurance runners (28). Expansion of total blood volume and RBCV as presently observed thus seems partially responsible for the 13.2% increase in $\dot{V}O_{2peak}$ (15). The present study did not measure any additional factors that might have contributed to increases in $\dot{V}O_{2peak}$ but it is possible that mitochondrial biogenesis and capillary vascularity might also be increased (29,30).

Our present level of red blood cell and total blood volume expansion is similar to other exercise training studies that observed increased total blood volume (31,32). Endurance exercise training induces an 8%–10% increase in vascular volume through a rapid plasma volume (PV) expansion that leads to an erythrocyte volume expansion within 2 to 3 wk to reestablish hematocrit levels (33). Warburton et al. (17) reported that blood volume (~10%) and RBCV (~12%) were significantly improved after 12 wk of HIIT, composed of repetitions of 2 min at 90% of $\dot{V}O_{2max}$ and 2 min at 40% of $\dot{V}O_{2max}$. In addition, Marterer et al. (34) reported that 6 wk of cycling training, consisting of 4 intervals of 4 min at 85%–95% of HR_{max} interspersed by 2 min cycling at 65%–75% of $\dot{V}O_{2max}$, significantly increased blood volume (+7.9%), total hemoglobin mass (+6.2%), and erythrocyte volume (+3.9) when compared with baseline values. We observed an increase in total blood volume (i.e., +7.5%) and RBCV (i.e., +5%) with higher training intensity (i.e., 80%–90% of P_{max}; corresponding to 400% $\dot{V}O_{2peak}$)

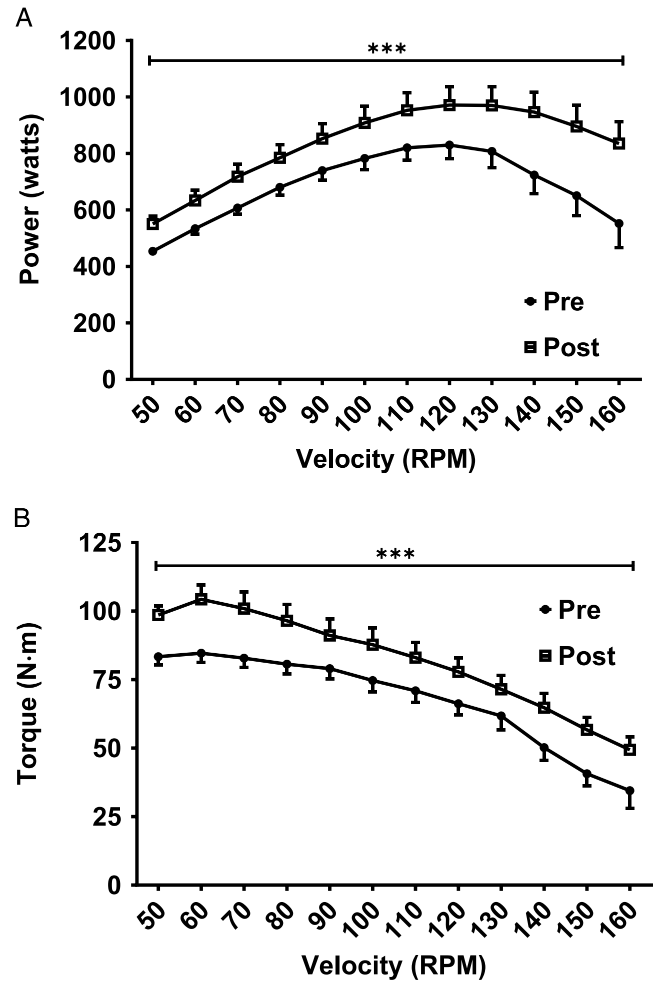

FIGURE 3—A, Mean power vs velocity plot during maximal anaerobic power tests on the inertial-load ergometer Pre and Post 8 wk of PC training. B, Mean torque vs velocity plot during maximal anaerobic power tests on the inertial-load ergometer. Values are means ± SEM before and after training (*n* = 11) (*P < 0.0001).**

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and lower training volume; <10 min of time and 2 min of actual exercise per session. The total oxygen-carrying capacity of RBC are critical at intensities that elicit $\dot{V}O_{2max}$ (15) and it has been shown that increased RBCV and PV can improve aerobic performance independently (28,35). It, thus, appears that the present PC training program is a most time efficient method for raising total blood volume and RBCV and possibly $\dot{V}O_{2peak}$.

High intensity exercise redirects blood flow away from the kidneys, which can cause renal hypoxemia and this effect is aggravated as exercise intensity increases (36). Low oxygen levels in the kidneys stimulate the production of erythropoietin to initiate the production of red blood cells. The reduction in renal blood flow is related to the intensity of exercise and renal blood flow may fall to 25% of the resting values (37). Furthermore, it has been reported (38) that renal blood flow declines progressively during graded aerobic exercise. It is therefore possible that PC induced reductions in renal blood flow may have caused intermittent hypoxia to the kidneys and stimulated erythropoietin to increase red blood cell production.

The 4-s sprints while training were performed with near maximal effort and generated over 80% of P_{max}, even as the recovery duration was reduced (Fig. 1). To provide perspective, at the end of the training period, maximal power when rested (i.e., 1009 W) was ~444% of the aerobic power needed to elicit $\dot{V}O_{2peak}$ (i.e., 227 W). These high power outputs during the sprints were possible due to their short duration and reliance on high energy ATP-PCr stores (27). The general exercise prescriptions for HIIT in previous studies varied substantially but are often between 85% and 250% $\dot{V}O_{2peak}$ (2,3,6). The present 4-s intervals are more powerful and somewhat similar to Serpiello et al. (39) as they used 4-s running sprints, repeated 15 times with 20-s recovery between sprints and 4.5 min between sets, which amounted to only 60 s of exercise per session with a total number of 10 sessions in the study. However, $\dot{V}O_{2peak}$ did not increase in this sprint running study, and the authors commented that a greater volume of training might be necessary although they reported induced mitochondrial biogenesis (39). The present volume of 120 s of repeated sprint exercise, progressing to 15 s of recovery, proved effective for raising $\dot{V}O_{2peak}$ and blood volume and maximal aerobic power. Whether 120 s of PC sprint exercise is the shortest and most time efficient method of training remains to be determined, but is more effective than a total of 60 s of running sprints (39).

The present 4 s training bouts might be considered SIT, which typically uses 20 to 30 s of maximal effort, followed by a 4.5-min recovery period and with performance of four to six repetitions. Burgomaster and colleagues (6) reported that their training intensity of SIT was ~500 W, which is approximately 40% to 50% less than the current PC 4-s sprints. Fatigue due to muscle acidosis is prevalent during the 20- to 30-s sprints but the long recovery period that is needed to restore homeostasis removes most of the cardiovascular stimulus (40). Training over 4 to 8 wk using 30-s sprints raised $\dot{V}O_{2peak}$ by ~7% (6), whereas 20-s sprints raised $\dot{V}O_{2peak}$ by ~12% to 15% (7). The present 13.2% increase in $\dot{V}O_{2peak}$ with PC appears partly related to expansion of red blood cell volume ($r^2 = 0.58$; Fig. 2). As mentioned, it is likely that mitochondrial enzyme activity was also increased (30). It is not known if the improvements in power and $\dot{V}O_{2peak}$ would have continued with training beyond the 8 wk.

The 4-s sprint PC bouts involved maximally accelerating the ergometer flywheel from 0 RPM up to 160 to 170 RPM and thus training was performed throughout the full range of the torque-velocity curve. As shown in Figure 3, maximal torque and power after training increased throughout the full continuum of the torque versus velocity relationship. This observation generally agrees with the concept of "specificity of training" in that all velocities underwent training and thus maximal torque production as well as power increased significantly at all cycling velocities. However, within that pattern, the increases in maximal torque and power were relatively larger at higher velocities (i.e., 35% at 140–160 RPM) compared with lower velocities (i.e., 15%–20% at 50–130 RPM). This pattern of torque and power improving the most at the highest speeds agrees with the previous observations using high speed isokinetic training that reported hypertrophy of type II muscle fibers (26). The present study has observed a 2.0-kg increase in body weight among participants and it is possible that part of this was a gain in muscle mass, although we have no direct data to support this possibility.

A limitation of the present study is a lack of a control group to identify potential fluctuations in the training group that might have been due to factors other than training. Fortunately, the increases in $\dot{V}O_{2peak}$ and blood volume were robust (i.e., 7%–13%) and larger than the error of the methods. How these results in young adults apply to other age groups, such as older adults has been recently tested with very similar results to the present study (41). We have no direct data regarding the sustainability of the program after 8 wk, but if it is any indication, almost all of the subjects appeared eager to continue training. Not having performed body composition on the subjects, we do not know the composition of the 2-kg body weight gain. Approximately 20% of that increase was in blood volume. We suspect that increases in leg muscle mass contributed significantly (41), but presently have no direct data. We have previously shown that these repeated 4-s sprints performed hourly in blocks of five throughout the day, stimulate reductions in postprandial plasma triglycerides, as well as increased fat oxidation (14). However, we did not measure fat metabolism in the present study to identify a potential training response.

In conclusion, we have shown that a program employing 30 bouts of 4-s inertial-load PC training with progressively reduced recovery time (30 to 24 to 15 s) between sprints is effective for improving total blood volume and red cell volume, $\dot{V}O_{2peak}$ and maximal anaerobic cycling power. This occurred with only 2 min of exercise in a < 10-min period during which perceived exertion did not become "very hard." Thus, inertial load PC cycle training involving repeated 4-s bouts of cycling at maximal effort is a unique program that is especially suited for people with limited time to exercise.

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