Heavy-, Severe-, and Extreme-, but Not Moderate-Intensity Exercise Increase $\dot{V}o_{2max}$ and Thresholds after 6 wk of Training

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ABSTRACT

INGLIS, E. C., D. IANNETTA, L. RASICA, M. Z. MACKIE, D. A. KEIR, M. J. MACINNIS, and J. M. MURIAS. Heavy-, Severe-, and Extreme-, but Not Moderate-Intensity Exercise Increase $\dot{V}o_{2max}$ and Thresholds after 6 wk of Training. *Med. Sci. Sports Exerc.*, Vol. 56, No. 7, pp. 1307–1316, 2024. **Introduction:** This study assessed the effect of individualized, domain-based exercise intensity prescription on changes in maximal oxygen uptake ($\dot{V}O_{2max}$) and submaximal thresholds. **Methods:** Eighty-four young healthy participants (42 females, 42 males) were randomly assigned to six age, sex, and $\dot{V}O_{2max}$-matched groups (14 participants each). Groups performed continuous cycling in the 1) moderate (MOD), 2) lower heavy (HVY1), and 3) upper heavy-intensity (HVY2) domain; interval cycling in the form of 4) high-intensity interval training (HIIT) in the severe-intensity domain, or 5) sprint-interval training (SIT) in the extreme-intensity domain; or no exercise for 6) control (CON). All training groups, except SIT, were work-matched. Training participants completed three sessions per week for 6 wk with physiological evaluations performed at PRE, MID, and POST intervention. **Results:** Compared with the change in $\dot{V}O_{2max}$ ($\Delta\dot{V}O_{2max}$) in CON (0.1 ± 1.2 mL·kg^{-1}·min^{-1}), all training groups, except MOD (1.8 ± 2.7 mL·kg^{-1}·min^{-1}), demonstrated a significant increase ($P < 0.05$). HIIT produced the highest increase (6.2 ± 2.8 mL·kg^{-1}·min^{-1}) followed by HVY2 (5.4 ± 2.3 mL·kg^{-1}·min^{-1}), SIT (4.7 ± 2.3 mL·kg^{-1}·min^{-1}), and HVY1 (3.3 ± 2.4 mL·kg^{-1}·min^{-1}), respectively. The ΔPO at the estimated lactate threshold (θ_{LT}) was similar across HVY1, HVY2, HIIT, and SIT, which were all greater than CON ($P < 0.05$). The $\Delta\dot{V}O_2$ and ΔPO at θ_{LT} for MOD was not different from CON ($P > 0.05$). HIIT produced the highest ΔPO at maximal metabolic steady state, which was greater than CON, MOD, and SIT ($P < 0.05$). **Conclusions:** This study demonstrated that i) exercise intensity is a key component determining changes in $\dot{V}O_{2max}$ and submaximal thresholds and ii) exercise intensity domain-based prescription allows for a homogenous metabolic stimulus across individuals.
Key Words: ENDURANCE TRAINING, EXERCISE INTENSITY DOMAINS, TRAINING ADAPTATIONS, EXERCISE PRESCRIPTION

Intensity is a key component of exercise training that can be manipulated by altering movement speed or power output (PO). As these prescriptive variables increase, the muscle metabolic response to the imposed energetic demand changes in ways that alter the intramuscular concentrations of key metabolites (e.g., adenosine diphosphate, inorganic phosphate, lactate, protons), which determine the metabolic disturbance within the muscle (1–5). The magnitude of the metabolic disturbance relates directly to the upregulation of signaling pathways responsible for the adaptative responses to exercise training that improve aerobic capacity and function (6). Thus, effective exercise prescription should follow a framework that can accurately predict, for any individual, the speed or PO to target a given metabolic disturbance. However, the most commonly used endurance exercise intensity prescription approaches do not guarantee such accuracy (7–9).

In research and clinical practice, exercise intensity prescription is commonly based on percent of maximal values of variables such as oxygen uptake ($\dot{V}O_{2max}$), heart rate (HR_{max}), their reserve equivalents, or peak work rate achieved during an incremental test to task failure. This approach is widely used in the field of exercise science to inform physical activity guidelines, clinical practice, and research designs to assign exercise training targets and to elucidate the impact of endurance exercise training intensity on maximal and submaximal variables (10–12). The purpose of this classification system is to

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normalize intensity between individuals varying in fitness. A key assumption is that prescription of relative intensity as a fraction of its maximum will elicit a common metabolic disturbance within the muscle for different individuals. However, interindividual variability in the metabolic and physiological responses to acute exercise at fixed percentages of $\dot{V}O_{2max}$ (and HR_{max}) refutes this assumption, highlighting a need for a paradigm shift in the way exercise is prescribed (7–9).

Interindividual variability in the underlying metabolic disturbance (and thus, the metabolic and physiological responses) occurs because this classification system does not take into consideration exercise thresholds and the exercise intensity domains they delineate (13–16). Specifically, these are the moderate- (i.e., below the lactate threshold (LT)), heavy- (i.e., between the LT and the maximal metabolic steady state (MSSS)), severe-, and extreme- (i.e., above the MMSS) intensity domains (3,17,18). Exercise within each domain elicits unique $\dot{V}O_2$ responses indicative of distinct changes in the way muscle metabolism responds and meets the energetic demands of exercise (3,18).

Although the metabolic responses within each domain are consistent between individuals, the specific position of the thresholds that demarcates their boundaries varies widely from person to person. For instance, at the same percentage of maximal values, different individuals could be exercising in two or even three different exercise intensity domains because the relative positions of LT and MMSS range from ~45% to 75% $\dot{V}O_{2max}$ and ~65% to 95% $\dot{V}O_{2max}$, respectively (13). Consequently, exercise at a given percentage of maximal values cannot guarantee domain-specific exercise or a homogeneous metabolic disturbance (13,16). This complicates the interpretation of many previous exercise training studies that have used percent of maximal responses for exercise prescription because the metabolic disturbance elicited by each session determines the acute responses and chronic adaptations (6,7,9,13). For example, heterogeneity in training responsiveness has largely been related to genetics (19); however, the contribution of genetics to such variability can only be assessed if the exercise intensity across individuals is consistent in an endurance exercise training intervention.

The limitations of the percent of maximal value approach for exercise prescription are well documented (3), but only some studies have adopted alternative individualized methods (i.e., accounting for the ventilatory/lactate thresholds (20–24)), and just a few have attempted to apply the domain-based framework in exercise training interventions (25,26). However, these studies have applied methods that are predisposed to errors in domain classification (e.g., assigning intensity based on HR [13,27] and/or not applying corrections when prescribing constant work rate exercise from incremental tests [28,29]) or have compared adaptations of only two, rather than all four, of the exercise intensity domains without including a control group (25,26). Thus, the present study aimed to assess the effect of exercise intensity on $\dot{V}O_{2max}$ and submaximal thresholds through individualized, domain-based exercise prescription. We hypothesized that domain-specific exercise prescription would elicit intensity-dependent increases in $\dot{V}O_{2max}$ and the thresholds demarcating exercise intensity domains.

METHODS

Participants

Ninety-nine young healthy females (n = 49) and males (n = 50) volunteered and provided written informed consent to participate after completing the Physical Activity Readiness Questionnaire and being cleared for exercise by a certified exercise physiologist. Fifteen of these participants were unable to complete the study because of illness/injury (n = 5), COVID-19–related precautions (n = 4), or other personal reasons (n = 6). Eighty-four participants (42 females, 42 males) completed the study. Participants ranged from sedentary (i.e., not regularly participating in physical activity and/or not meeting physical activity guidelines) to recreationally active (i.e., reporting <3 $d \cdot wk^{-1}$ of unstructured physical activity). Participants were randomized (stratified randomization based on sex) at a ratio of 1:6 into the control group (CON) (n = 14) or one of the five cycling-based exercise training intervention groups (n = 70). All procedures included in this study were approved by the Conjoint Health Research Ethics Board at the University of Calgary. The data presented in this study are part of a randomized training study, entitled Modifying the Exercise Guideline Approach (MEGA), investigating the impact of domain-specific exercise intensity prescription on a number of physiological variables. This is the first report of the results from the MEGA study.

Equipment

A metabolic cart and mixing chamber (Quark CPET; COSMED, Rome, Italy) were used to measure gas exchange and ventilatory variables continuously during testing. Fractional concentrations of oxygen (O_2) and carbon dioxide (CO_2) were measured continuously at the mixing chamber by paramagnetic and nondispersive infrared analyzers, respectively. Expired volume was monitored by a bidirectional digital turbine (resistance: <0.6 cm $H_2O \cdot L^{-1} \cdot s^{-1}$ at 14 $L \cdot s^{-1}$) placed at the inlet of the chamber. Participants wore a facemask that was fit via a special connector to a non-rebreathing valve. A large-bore hose attached to the expiratory end of the non-rebreathing valve was connected to the metabolic cart. Gas exchange and ventilatory variables were calculated in 10-s time intervals. Before each testing session, gas and flow calibrations were performed using a compressed gas cylinder of known concentration (16% O_2 and 4% CO_2) and a 3-L volume syringe according to manufacturer recommendations. Heart rate (HR) was also monitored continuously during testing and training sessions (Garmin, Chicago, IL). Capillary blood samples obtained from a pinprick of the finger were used to measure blood lactate concentration ($[La^-]$) (Biosen C-Line; EKF Diagnostics, Barleben, Germany).

All testing and training sessions (apart from sprint interval training (SIT)) were performed using the Tacx NEO Smart

Trainers (Garmin) with custom, adjustable bike frames. A tablet and the Golden Cheetah software (version 3.4; https://www.goldencheetah.org/) was used to control the protocols. One NEO Smart Trainer and frame was designated as the testing ergometer, and the others were used for training only. Each participant was assigned to a training station, and this was kept consistent throughout the study. For all training and testing sessions with the NEO system, participants were asked to maintain their preferred cadence between 70 and 95 rpm. SIT was performed on an electromagnetic-braked cycle ergometer (Velotron; RacerMate, Seattle, WA) using the Wingate software v1.0 (Racermate).

Experimental Timeline and Protocols

Participation in the study was approximately 11.5 wk as presented in Figure 1. Testing phases occurred before (PRE), between (MID), and immediately after (POST) two, 3-wk training phases (6 wk total). MID testing was used to monitor and adjust exercise training intensities (these data are not presented). Each testing phase consisted of one ramp incremental maximal session and 2–3 sessions to determine MMSS. Time of the day for the testing sessions was kept consistent (±1 h) for each participant at PRE, MID, and POST. A minimum of 24 h separated the $\dot{V}O_{2max}$ from the first MMSS session, whereas 48–72 h separated subsequent MMSS trials.

Maximal session. A cycling ramp incremental test (females, 20 W·min^{-1}; males, 25 W·min^{-1}) was performed to task failure to measure $\dot{V}O_{2max}$, HR_{max}, peak power output (PPO), estimated LT (θ_{LT}), and the respiratory compensation point (RCP). The ramp-incremental test was preceded by an 8-min moderate step transition from a 30-W baseline (3-min) to 60–80 W depending on the individual. Then, after a 3-min rest, participants performed a 4-min baseline at 30 W before the ramp portion of the test began and was sustained until task failure. Task failure was defined as the point at which participants could not continue to cycle or when there was a drop in cadence below 65 rpm for more than 5 consecutive seconds, despite strong verbal encouragement. Following a brief recovery period (~7–10 min), participants then performed a constant work rate trial, which consisted of a 2-min baseline at 30 W followed by square wave step transition to ~80%–85% of PPO performed to volitional exhaustion. This trial was used to induce maximal responses for a separate aim of the MEGA trial not reported here. Blood lactate ([La$^-$]) samples were taken immediately at the end of both the ramp-incremental test and the trial at ~80%–85% of PPO.

MMSS sessions. To determine the PO associated with MMSS, participants completed 2–3 constant PO exercise trials. Each trial started with 4-min baseline cycling at 30 W, after which the PO was instantaneously increased to a predetermined PO for 30 min. For these trials, [La$^-$] was measured at 5-min intervals, and $\dot{V}O_2$ was measured continuously. The PO for the initial trial was determined using a predictive equation based on measured RCP (30), and the PO for subsequent trial(s) was increased or decreased based on the [La$^-$] and $\dot{V}O_2$ responses. Blood [La$^-$] samples were taken in duplicate or triplicate starting at baseline and at 5-min intervals thereafter. Triplicate samples were taken at the 15th and 30th minutes. Each time point was represented by the average of the two available samples or the average of the two closest samples when taken in triplicate. MMSS was determined to be the highest PO at which stable responses in both [La$^-$] and $\dot{V}O_2$ were achieved between the 15th and 30th minutes as previously defined (31). To minimize the margin of error for measures of the PO at MMSS, a 5% difference in PO was used between trials.

FIGURE 1—Study timeline delineating the PRE-, MID-, and POST-training testing periods, as well as the two 3-wk blocks of exercise training.

Exercise Training Prescription

Both exercise training phases were 3 wk in duration, with 3 sessions per week for a total of 9 sessions per phase and 18 sessions by the end of the program. Exercise training was completed Monday through Saturday, and participants were asked to have at least 24 h of recovery between subsequent sessions and at least one 48-h rest period within each week (i.e., training 3 d in a row was not permitted). Training adherence across all intervention groups was 98% ± 5%. The intensities of the five cycling exercise conditions were: i) constant-PO in the moderate-intensity domain (MOD), ii) constant-PO in the lower boundary of the heavy-intensity domain (HVY1), iii) constant-PO in the upper boundary of the heavy-intensity domain (HVY2), iv) high-intensity interval training (HIIT) in the severe-intensity domain, and v) and SIT in the extreme-intensity domain.

The MOD group performed 50 min of cycling at 90% of the PO at θ_{LT}, This duration was chosen so that this group would meet well-established physical activity guidelines for individuals aiming to become active and/or maintain health rather than training for sport performance (11). HVY1 performed ~41 min at 110% of the PO at θ_{LT}, and HVY2 performed ~30 min at 100% of the PO at MMSS. The HIIT group performed five to six intervals lasting 4 min interposed by 3 min of recovery. The PO during the work and rest phases corresponded to ≥120% of MMSS and ~30% of MMSS, respectively, and both phases were included in the work calculation. The total work targets in HVY1, HVY2, and HIIT were individually work-matched to the total work of each participants' MOD (i.e., 50 min of cycling at 90% of the PO at θ_{LT}). The MOD, HVY1, HVY2, and HIIT groups all performed a standardized 2-min baseline at 55% of θ_{LT}. SIT consisted of up to six, 30-s maximal all-out sprints with no pacing strategy against a fixed resistance (0.06–0.075 kg–kg^{-1} of body mass) with 4.5 min of unloaded cycling (up to 20 W) or rest between sprints. The SIT warm-up consisted of 10 min cycling at 50 W with three, 3-s practice sprints interspaced within the later half of the

warm-up. Participants in the SIT group started with three sprints. The number of sprints per session was progressively increased by a minimum of one sprint per week until six sprints were performed by week 4.

Data Analysis

Raw ventilatory and gas-exchange data for each participant were independently evaluated by two experts to identify the $\dot{V}O_2$ corresponding to the θ_{LT} and RCP. In case of a disagreement of >100 $mL \cdot min^{-1}$, the profiles were reevaluated by both experts together until an agreement was reached. The θ_{LT} and RCP were established as detailed elsewhere (32). In short, the θ_{LT} was identified as the point at which i) carbon dioxide production ($\dot{V}CO_2$) began to increase disproportionally in relation to $\dot{V}O_2$, ii) there was a systematic rise in the ventilation ($\dot{V}_E$) versus $\dot{V}O_2$ relationship and partial pressure of expired oxygen (P_EO_2), and iii) there was stability in the ventilatory equivalent of $\dot{V}CO_2$ ($\dot{V}_E/\dot{V}CO_2$) and partial pressure of expired carbon dioxide (P_ECO_2) (33). The RCP was established to occur at the point at which there was a systematic fall in P_ECO_2 following a period of isocapnic buffering (34). Confirmation of the RCP was achieved by a second breakpoint in the $\dot{V}_E$ versus $\dot{V}O_2$ and examining the $\dot{V}_E/\dot{V}CO_2$ versus $\dot{V}O_2$ relationship and ventilatory equivalent of $\dot{V}O_2$ ($\dot{V}_E/\dot{V}O_2$) versus $\dot{V}O_2$ relationship.

$\dot{V}O_2$ data were first filtered by removing aberrant points that fell 3 SDs from the local mean before being linearly interpolated on a second-by-second basis. The $\dot{V}O_2$ mean response time was calculated using the moderate step transition performed before the ramp-incremental test as previously described (35). In brief, a linear fit was applied to the ramp-incremental test $\dot{V}O_2$ data from the ramp onset to the established θ_{LT}. Then, the $\dot{V}O_2$ of the moderate step transition (average of the last 2 min) was superimposed on the $\dot{V}O_2$ versus PO relationship from the ramp. The difference in PO corresponding to the abscissa identified during the ramp linear fit versus that of the moderate-step transition was then converted to time, which was then used to align the ramp-incremental $\dot{V}O_2$ with the corresponding PO and allowed for the identification of PO at the θ_{LT}. $\dot{V}O_{2max}$ was defined as the highest 20-s rolling average achieved during the ramp incremental test or the constant work rate trial.

Statistics

Data are presented as mean ± SD. Normality of the distribution was verified for all dependent variables. A two-way mixed ANOVA was used to compare the effect of time (PRE vs POST) and group (CON, MOD, HVY1, HVY2, HIIT, vs SIT) on the variables of interest. Significance among multiple comparisons was confirmed using Tukey's *post-hoc* tests. Effect sizes are reported as partial eta-squared (partial η^2), where values of 0.01, 0.06, and 0.14 correspond to small medium and large effects, respectively (36). A one-way ANOVA was performed to compare baseline characteristics of the control and intervention groups as well as to compare delta changes at POST between groups. Tukey's *post-hoc* tests were used to perform the pairwise between-group comparisons. The 95% confidence interval (CI) of the mean for the delta (Δ) increase in $\dot{V}O_{2max}$ was calculated for CON. Statistical analyses were performed using SPSS Statistics v. 26.0 (SPSS; IBM, Chicago, IL).

RESULTS

At PRE, all groups were evenly matched for age ($P = 0.91$), height ($P = 0.75$), and body mass ($P = 0.90$; Table 1). In addition, there were no between-group differences in $\dot{V}O_{2max}$ ($P = 0.87$) and PPO ($P = 0.87$), or in the $\dot{V}O_2$ values at θ_{LT} ($P = 0.67$), MMSS ($P = 0.79$), or their corresponding PO values ($P = 0.62$ for θ_{LT} and $P = 0.75$ for MMSS; see Table 2).

Compared with PRE, body mass remained unchanged at POST in all groups ($F(5,78) = (1.70$, $P = 0.145$, $\eta^2 = 0.10$, 0.00–0.16); Table 1). In CON, there were no pre- versus post-changes in any measured outcomes. Except for the CON group, PRE to POST increases were observed in all exercise training groups for $\dot{V}O_{2max}$ ($F(5,78) = (13.78$, $P < 0.001$, $\eta^2 = 0.47$, 0.30–0.54)), PPO ($F(5,78) = (5.59$, $P < 0.001$, $\eta^2 = 0.57$, 0.42–0.64)), and ramp-incremental duration ($F(5,78) = (25.04$, $P < 0.001$, $\eta^2 = 0.62$ (0.48–0.68); Table 2). When comparing the Δ increase in $\dot{V}O_{2max}$, all training groups, except MOD, demonstrated significant increases compared with CON ($P < 0.05$; Fig. 2). HIIT training produced the largest Δ increase in $\dot{V}O_{2max}$ followed by HVY2, SIT, and HVY1, respectively. The $\Delta\dot{V}O_{2max}$ increases in HIIT, HVY2, and SIT were significantly greater than that observed in MOD. In addition, HIIT demonstrated a greater Δ increase in $\dot{V}O_{2max}$ than HVY1 ($P < 0.05$). Compared with CON, the Δ increase in PPO and ramp-incremental duration was significant for all intervention groups ($P < 0.05$). HIIT produced the largest Δ increase in PPO and ramp-incremental duration, which was greater than that of MOD, HVY1, and SIT ($P < 0.05$). HVY2 resulted in a greater Δ increase in PPO and ramp-incremental duration compared with MOD and SIT ($P < 0.05$).

When comparing PRE to POST values in each intervention group, the $\dot{V}O_2$ and PO at θ_{LT} increased ($F(5,78) = (5.59$, $P < 0.001$, $\eta^2 = 0.26$, 0.09–0.35) and $F(5,78) = (6.32$, $P < 0.001$, $\eta^2 = 0.29$, 0.12–0.38), respectively) as did the $\dot{V}O_2$ and PO at the MMSS ($F(5,78) = (3.83$, $P = 0.004$, $\eta^2 = 0.20$, 0.04–0.28) and $F(5,78) = (14.85$, $P < 0.001$, $\eta^2 = 0.49$, 0.32–0.56), respectively; Table 2; Figs. 3A, B). Except for MOD, which resulted in no significant Δ increases compared with CON, similar Δ increases in $\dot{V}O_2$ and PO at θ_{LT} were observed across all groups in relation to CON ($P < 0.05$). HIIT and SIT produced the greatest Δ increase in $\dot{V}O_2$ at MMSS, which was greater than in CON ($P < 0.05$). Changes in $\dot{V}O_2$ at MMSS in MOD, HVY1, and HVY2 were not different from CON ($P > 0.05$). All groups, except MOD, had a Δ increase in PO at MMSS that was greater than CON ($P < 0.05$). HIIT had the largest Δ increase in PO at MMSS,

TABLE 1. Participant characteristics.

	CON		MOD		HVY1		HVY2		HIIT		SIT	
	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST
Age, yrs	27 ± 5	—	25 ± 5	—	27 ± 6	—	26 ± 5	—	27 ± 8	—	28 ± 6	—
Height, cm	170 ± 7	—	167 ± 8	—	170 ± 8	—	169 ± 7	—	169 ± 11	—	172 ± 11	—
Body mass												
kg	68.9 ± 11.7	69.4 ± 11.6	66.4 ± 11.9	66.1 ± 11.3	71.7 ± 13.1	71.5 ± 11.9	68.3 ± 8.2	68.4 ± 8.1	70.2 ± 18.3	69.9 ± 17.0	73.9 ± 10.7	72.5 ± 11.1
Δ	0.4 ± 0.8		−0.4 ± 1.5		−0.2 ± 1.8		0.1 ± 1.7		−0.3 ± 2.6		−1.4 ± 1.6	

Values are mean ± SD.
CON, no training control group (n = 14; 7 females); MOD, moderate-intensity domain training (n = 14; 7 females); HVY1, lower boundary of the heavy-intensity domain training (n = 14; 7 females); HVY2, upper boundary of the heavy-intensity domain training (n = 14; 7 females); HIIT, high-intensity interval training in the severe-intensity domain (n = 14; 7 females); SIT, sprint interval training in the extreme-intensity domain (n = 14; 7 females).

which was greater than MOD and SIT ($P < 0.05$), followed by HVY2, HVY1, and SIT, respectively.

Figure 4 displays the $\dot{V}O_2$ and [La−] values during the constant load trials at MMSS and 5% above MMSS for participants who were able to complete at least 20 min in the 5% above MMSS trial.

DISCUSSION

This is the first study to apply the exercise intensity domain framework to investigate intensity domain–specific effects of aerobic exercise training on $\dot{V}O_{2max}$, the θ_{LT}, and MMSS. Five groups of 14 participants each completed 6 wk of either constant-PO training within the moderate (MOD), or lower or upper regions of the heavy-intensity domain (HVY1 and HVY2), or interval training in the form of HIIT or SIT in the severe- or extreme-intensity domains, respectively. MOD, HVY1, HVY2, and HIIT were work-matched, and PRE versus POST differences were compared between the domain-specific training groups and to a nonexercise training control group (CON). Novel findings were that i) MOD did not elicit a Δ increase in θ_{LT}, MMSS, and $\dot{V}O_{2max}$ greater than CON; ii) excluding SIT, the Δ changes in $\dot{V}O_{2max}$ were intensity-domain dependent, with progressively greater intensities within the heavy domain resulting in greater increases in $\dot{V}O_{2max}$, and HIIT eliciting the largest change; and iii) this intensity-domain dependency was less pronounced when evaluating changes in the θ_{LT} and MMSS and did not apply to the extreme-intensity domain (i.e., was not evident with SIT). In addition, exercise training intensities above the θ_{LT} led to a substantial reduction or an elimination in the number of individuals who did not produce $\Delta\dot{V}O_{2max}$ greater than the 95% CI in CON. Collectively, these data indicate that controlling the metabolic stimulus using physiologically established demarcation points is critically important when examining intensity-dependent effects on adaptations in maximal responses to endurance exercise training. Furthermore, the data suggest that there may be a minimal intensity stimulus needed to stimulate improvements in $\dot{V}O_{2max}$ and submaximal thresholds at the group and individual level.

TABLE 2. Maximal and submaximal physiological variables at PRE and POST.

	CON		MOD		HVY1		HVY2		HIIT		SIT	
	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST
$\dot{V}O_{2max}$												
mL·kg^{-1}·min^{-1}	42.7 ± 6.0	42.8 ± 5.7	41.1 ± 5.7	42.9 ± 4.7[a]	40.1 ± 5.5	43.4 ± 5.4[a]	40.9 ± 4.8	46.2 ± 4.4[a]	40.2 ± 6.2	46. 4 ± 6.8[a]	40.9 ± 6.6	45.6 ± 6.9[a]
Δ mL·kg^{-1}·min^{-1}	0.1 ± 1.2		1.8 ± 2.7		3.3 ± 2.4[b]		5.4 ± 2.3[b,c]		6.2 ± 2.8[b,c,d]		4.7 ± 2.3[b,c]	
PPO												
Watts	240 ± 50	240 ± 51	221 ± 49	238 ± 49[a]	231 ± 51	257 ± 56[a]	228 ± 40	264 ± 39[a]	213 ± 57	261 ± 65[a]	247 ± 52	266 ± 55[a]
Δ Watts	0 ± 8		17 ± 8[b]		26 ± 14[b]		36 ± 10[b,c,e]		48 ± 23[b,c,d,e]		19 ± 13[b]	
Ramp-incremental duration												
Minutes	9.3 ± 1.6	9.3 ± 1.6[a]	8.4 ± 1.5	9.1 ± 1.5[a]	8.9 ± 1.8	10.0 ± 1.9[a]	8.8 ± 1.4	10.4 ± 1.2[a]	8.0 ± 1.9	10.2 ± 2.1[a]	9.6 ± 1.8	10.4 ± 1.7[a]
Δ Minutes	−0.0 ± 0.3		0.7 ± 0.3[b]		1.1 ± 0.6[b]		1.6 ± 0.4[b,c,e]		2.1 ± 0.9[b,c,d,e]		0.8 ± 0.5[b]	
θ_{LT}												
mL·kg^{-1}·min^{-1}	23.8 ± 3.3	24.1 ± 3.3	22.6 ± 3.5	24.8 ± 3.5[a]	22.3 ± 2.8	25.8 ± 3.2[a]	24.8 ± 3.4	28.3 ± 3.1[a]	23.8 ± 3.7	27.3 ± 3.6[a]	22.3 ± 3.2	26.0 ± 4.0[a]
Δ mL·kg^{-1}·min^{-1}	0.3 ± 1.3		2.2 ± 2.1		3.4 ± 1.8[b]		3.5 ± 1.8[b]		3.6 ± 1.9[b]		3.7 ± 2.4[b]	
Watts	94 ± 18	97 ± 22	87 ± 27	103 ± 27[a]	93 ± 22	119 ± 27[a]	105 ± 31	131 ± 27[a]	95 ± 29	119 ± 32[a]	95 ± 24	120 ± 26[a]
Δ Watts	3 ± 10		16 ± 10		25 ± 12[b]		26 ± 13[b]		24 ± 14[b]		25 ± 20[b]	
MMSS												
mL·kg^{-1}·min^{-1}	35.3 ± 5.1	35.7 ± 4.4	33.5 ± 4.4	35.6 ± 4.4[a]	33.2 ± 4.5	35.2 ± 4.7[a]	35.2 ± 4.6	38.0 ± 4.5[a]	33.3 ± 6.7	37.6 ± 7.5[a]	33.1 ± 5.6	36.4 ± 6.2[a]
Δ mL·kg^{-1}·min^{-1}	0.5 ± 1.8		2.2 ± 2.3		2.0 ± 2.6		2.7 ± 2.3		4.3 ± 2.8[b]		3.3 ± 1.6[b]	
Watts	141 ± 33	143 ± 34	125 ± 31	136 ± 33[a]	133 ± 33	152 ± 36[a]	136 ± 35	156 ± 32[a]	123 ± 45	152 ± 48[a]	137 ± 36	153 ± 39[a]
Δ Watts	2 ± 6		11 ± 6		19 ± 10[b]		20 ± 9[b]		28 ± 9[b,c,e]		16 ± 11[b]	

Values are mean ± SD.
[a] Significantly different from PRE.
[b] Significantly different from CON.
[c] Significantly different from MOD.
[d] Significantly different from HVY1.
[e] Significantly different from SIT.
CON, no training control group (n = 14; 7 females); MOD, moderate-intensity domain training (n = 14; 7 females); HVY1, lower boundary of the heavy-intensity domain training (n = 14; 7 females); HVY2, upper boundary of the heavy-intensity domain training (n = 14; 7 females); HIIT, high-intensity interval training in the severe-intensity domain (n = 14; 7 females); SIT, sprint interval training in the extreme-intensity domain (n = 14; 7 females).

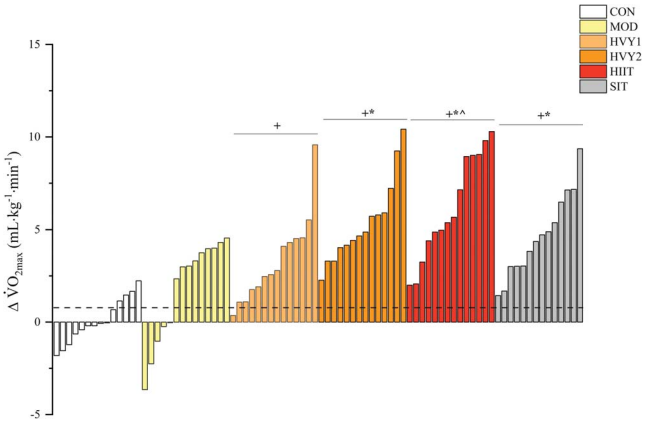

FIGURE 2—Individual delta (Δ) changes in $\dot{V}O_{2max}$ at POST following 6 wk of training presented in order of the magnitude of their responses within each group. CON, no training control group (n = 14; 7 females); MOD, moderate-intensity domain training (n = 14; 7 females); HVY1, lower boundary of the heavy-intensity domain training (n = 14; 7 females); HVY2, upper boundary of the heavy-intensity domain training (n = 14; 7 females); HIIT, high-intensity interval training in the severe-intensity domain (n = 14; 7 females); SIT, sprint interval training in the extreme-intensity domain (n = 14; 7 females). Dashed horizontal line indicates the upper 95% confidence interval of CON. Statistical significance based on group values: +significantly different from CON, *significantly different from MOD, ^significantly different from HVY1.

$\dot{V}O_{2max}$ responses. The novelty of this study is that the design provided insight into the role of exercise intensity domains and their known differences in metabolic disturbances, on changes in maximal and submaximal aerobic fitness/performance. This was possible because the precise exercise intensity prescription ensured that each intensity domain was represented by an intervention group (i.e., MOD, HVY1, HVY2, HIIT, and SIT) and that, except for SIT, the total amount of work was matched. In this regard, a key finding is that, although MOD elicited a small but significant average increase in $\dot{V}O_{2max}$ after exercise training (PRE to POST), the magnitude of this increase (i.e., Δ increase) was not significant when compared with CON. In other words, the magnitude of the overall increase in $\dot{V}O_{2max}$ following MOD did not exceed the variability observed in CON and therefore would not be considered a "true improvement." Conversely, the $\Delta\dot{V}O_{2max}$ for all the other groups were significantly greater compared with CON. These results are important to highlight because they refute the commonly accepted assumption that any exercise intensity can result in improvements in fitness, especially when evaluating changes in previously untrained participants (37).

A potential reason for this discrepancy might reside in the precise estimation of the exercise intensity performed in the current study compared with previous investigations. Specifically, there are evident misconceptions/disagreements about the definition of moderate-intensity exercise training, which is a common comparison group to high-intensity or sprint interval training (38,39). For example, moderate intensity is commonly prescribed as 60%–75% of $\dot{V}O_{2max}$ or HR_{max}; however, given that percentages of $\dot{V}O_{2max}$ or HR_{max} values have been shown to place different participants within different exercise intensity domains (13), it is likely that, by using such an approach, at least some of the participants would be prescribed heavy-intensity exercise. This is important to consider given that, as demonstrated in this study, heavy-intensity exercise produces different magnitude of adaptations compared with true sub-θ_{LT} moderate-intensity exercise. The limitations of using these approaches based on the percent of maximal responses have recently been highlighted by our group (13,15). Another source of error comes from differences in categorization used when referring to moderate-intensity exercise. For example, whereas in this study, moderate intensity was defined as being below the θ_{LT}, as originally proposed by Whipp (3), others consider it to be near the critical intensity of exercise (40), or simply any intensity of exercise that can be sustained for prolonged periods of time. Such inconsistencies in definitions and/or terminology impact our ability to determine which intensities of exercise are most beneficial for improving cardiorespiratory fitness. This issue has also been recently highlighted as an important factor to consider when establishing physical activity and exercise prescription guidelines (41).

The results from this study also demonstrated that the highest intensity of exercise for the work-matched groups (i.e., HIIT in the severe-intensity domain) produced the largest improvement in $\dot{V}O_{2max}$, which is in agreement with previous studies comparing HIIT versus continuous "moderate-intensity" training (22,25). Furthermore, the results indicated that there is an intensity domain–dependent improvement in $\dot{V}O_{2max}$ as, when total work was matched, the Δ increase was greater with progressive increases in intensity domain.

Importantly, this study also showed that if the prescribed exercise intensity was above the θ_{LT}, almost all participants displayed

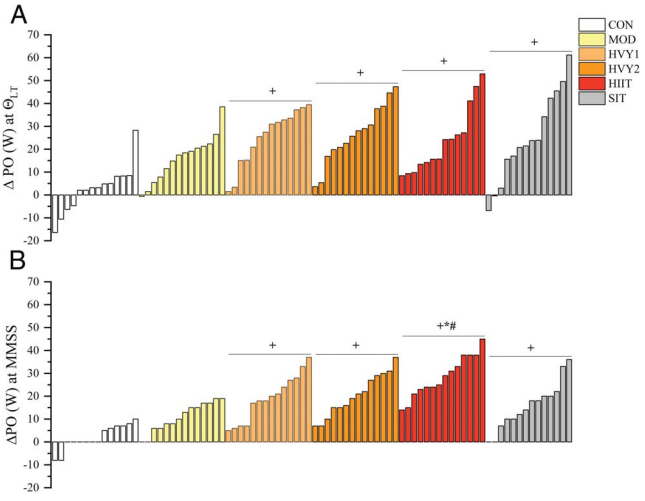

FIGURE 3—Individual delta (Δ) changes in PO at the estimated LT (θ_{LT}) (A) and the MMSS (B) at POST following 6 wk of training presented in order of the magnitude of their responses within each group. CON, no training control group (n = 14; 7 females); MOD, moderate-intensity domain training (n = 14; 7 females); HVY1, lower boundary of the heavy-intensity domain training (n = 14; 7 females); HVY2, upper boundary of the heavy-intensity domain training (n = 14; 7 females); HIIT, high-intensity interval training in the severe-intensity domain (n = 14; 7 females); SIT, sprint interval training in the extreme-intensity domain (n = 14; 7 females). Statistical significance based on group values: +significantly different from CON, *significantly different from MOD, #significantly different from SIT.

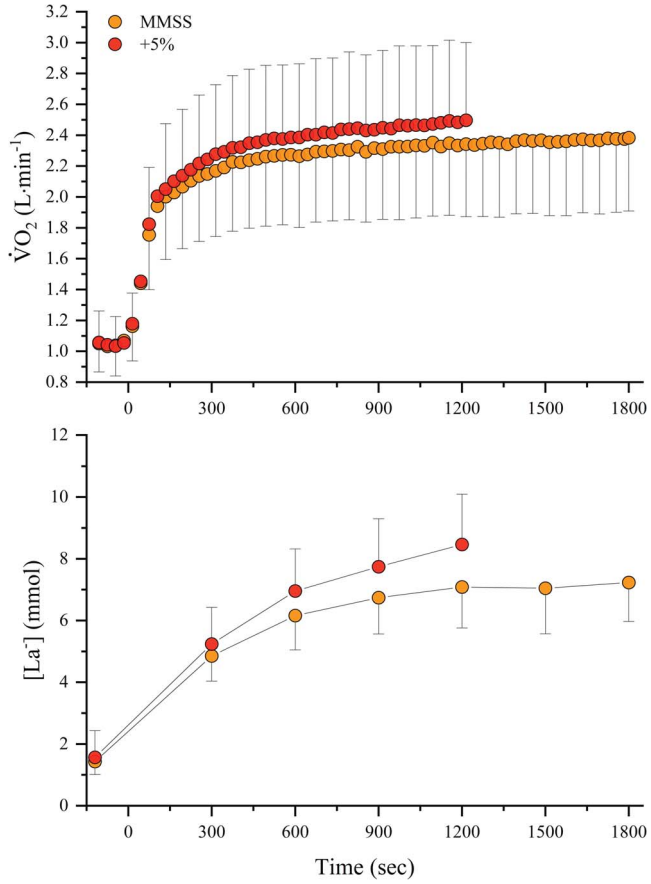

FIGURE 4—Oxygen uptake ($\dot{V}O_2$) and blood lactate ([La$^-$]) values during the constant load trials determined to be MMSS and above (+5%). Data presented represent the mean ± SD for participants who were able to complete at least 20 min in the 5% above MMSS trial (n = 53).

a positive response to the intervention. For example, in HVY1, HVY2, HIIT, and SIT combined, only 1 out of 56 participants had a $\Delta\dot{V}O_{2max}$ below the upper 95% CI of CON compared with 5 out of 14 participants in MOD (see Fig. 2). Thus, although genetic characteristics have been suggested to play a predominant role in the heterogeneous adaptations to exercise training (19), the prescription methods used to support such conclusions (i.e., HR associated with 55% and 75% of $\dot{V}O_{2max}$ from the preintervention testing) did not precisely control the intensity of exercise at the individual level. Considering this issue, along with the results from this study, exercise intensity is likely a key factor contributing to individual variability in response to training. Therefore, the implementation of exercise prescription based on the intensity domain framework would serve to remove the confounding variable of nonuniform exercise intensity prescription, thereby reducing the heterogeneity of individual training responsiveness, and allow for the true magnitude of the genetic component to be revealed.

Despite having the highest exercise intensity, SIT training did not produce the largest $\Delta\dot{V}O_{2max}$. Instead, similar to HVY1, SIT resulted in improvements that were significantly greater than CON, but not significantly different from MOD. This may be related to the exercise duration. Although we can assume that the magnitude of the acute metabolic perturbations of SIT is close to those produced by HIIT (42), the total duration of the stimulus in SIT (i.e., 1.5–3 min of sprinting) may not have been long enough to elicit exercise training–induced adaptations comparable to those of HIIT or HVY2 (26). This is important because comparisons of interval and continuous training (i.e., systematic reviews and meta-analyses) often combine results from HIIT and SIT under the same umbrella (43); however, in light of our findings, the assumption that HIIT and SIT are similar should be abandoned considering that HIIT is to be performed exclusively within the severe-intensity domain, whereas SIT is purely extreme-intensity domain exercise. Under these conditions, the potential to reach and sustain a $\dot{V}O_{2max}$ within the extreme-intensity domain is limited, and this may underpin the lower effectiveness of SIT in improving $\dot{V}O_{2max}$ compared with HIIT (17). Whereas this study demonstrates that SIT still improves $\dot{V}O_{2max}$ despite a much lower volume of exercise, it also provides important insight into how SIT compares to training in each intensity domain.

Although all groups (except SIT) performed the same amount of total work, the MOD group was the only group not displaying a significant Δ increase in $\dot{V}O_{2max}$ compared with CON despite achieving 150 min·wk^{-1} of moderate-intensity exercise. This indicates that there is likely a minimum-intensity stimulus needed to produce meaningful overall changes in $\dot{V}O_{2max}$ that exceed the variability of the measure in relation to a nonexercising control group, at least for the population studied herein. This is in line with previous research by Ross et al. (44) in which they concluded that achieving the minimum amount (i.e., time) and intensity of exercise recommended by guidelines may be insufficient to improve cardiorespiratory fitness. Interestingly, the other intervention groups in the present study demonstrated significant improvements across all variables with lower total weekly exercise times of ~120 (HVY1), ~90 (HVY2), ~60–72 (HIIT, excluding the low-intensity recovery), and ~18 (SIT) min. This suggests that the exercise guidelines for "vigorous" intensity exercise may be more appropriate for improving cardiorespiratory fitness compared with the guidelines for "moderate"-intensity exercise. Furthermore, from an exercise prescription standpoint, there was not a substantial difference between MOD and HVY1 with both falling ~10% below and above the θ_{LT}, respectively. However, despite this small difference, only HVY1 produced a significant Δ increase in $\dot{V}O_{2max}$ compared with CON. This result is similar to previous research that demonstrated that endurance training above the θ_{LT} produced significantly greater $\dot{V}O_{2max}$ values following an exercise training intervention compared with control, whereas endurance training at the θ_{LT} did not (45). Together, these results highlight the crucial role of exercise intensity for eliciting improvements in $\dot{V}O_{2max}$ and reinforce the idea that in sedentary and/or recreationally active individuals, an intensity prescription exceeding θ_{LT} might be required to elicit meaningful and consistent increases in $\dot{V}O_{2max}$.

Threshold responses. Similar to $\dot{V}O_{2max}$, PRE to POST differences were detected in all intervention groups for $\dot{V}O_2$

and PO at θ_{LT} and MMSS. However, compared with CON, there was a similar Δ increase in the $\dot{V}O_2$ and PO at θ_{LT} across all groups exercising above the θ_{LT}, whereas MOD did not significantly increase. This provides further support to the notion of a minimal intensity stimulus needed for improvements in both maximal and submaximal thresholds. In addition, these results suggest that for a submaximal variable such as the θ_{LT}, once a certain level of intensity is provided (i.e., training above the θ_{LT}), further increases in intensity do not result in progressively greater magnitude of increase. Although an improvement in θ_{LT} is a beneficial submaximal adaptation that could have important functional implications in previously untrained young and older participants and/or in clinical populations, increases in θ_{LT} might reach an upper limit without accompanying increases in $\dot{V}O_{2max}$. In other words, the $\%\dot{V}O_{2max}$ at which the θ_{LT} occurs (typically ~55%–65% of $\dot{V}O_{2max}$ in untrained/moderately trained individuals (13,46)) may not be continuously increased beyond a certain normal range of maximal responses.

The PO at MMSS is an important outcome as it represents the highest work rate at which oxidative metabolism can almost completely support a task. When evaluating the PO at MMSS, MOD was the only group that did not show a significant Δ increase compared with CON. Conversely, HVY1, HVY2, and SIT produced a similar Δ increase compared with CON, whereas HIIT produced the greatest Δ increase. This result is additional evidence in support of the idea of a minimal intensity stimulus needed to elicit improvements in $\dot{V}O_{2max}$ as well as in submaximal thresholds. Moreover, these data provide evidence that, unlike the θ_{LT}, higher intensities of exercise that properly control for the metabolic disturbance can produce a greater Δ increase for MMSS, as observed in HIIT; however, intensity alone may not be the determining factor as SIT, which had the highest intensity, did not produce the greatest Δ change. Instead, the fact that HIIT had a high level of intensity combined with a longer duration (i.e., a greater time exposure to the stimulus) may be the reason why it was the group that elicited the largest increase in PO at MMSS, whereas the other groups (except MOD) had similar changes. Finally, it is important to note that the results of this study indicate that not only did HIIT have the largest magnitude of improvements, but that it produced improvements across all variables measured, whereas the other training groups did not.

Practical application. This study is the first to demonstrate the role of domain (i.e., metabolic disturbance) specific exercise intensity on changes in $\dot{V}O_{2max}$ and submaximal thresholds compared with a control group. The results of this study should be used by researchers/professionals to better direct their exercise training interventions and by groups/organizations to develop more evidence-based, individualized physical activity/exercise prescription guidelines that consider the importance and implications of accurate exercise intensity prescription using the intensity domain framework. Importantly, although these results and interpretations come from young healthy individuals, it is reasonable to expect that similar results would also be found in clinical and elderly populations. This is because current prescription guidelines for the elderly and clinical populations share the same shortcomings of the approaches used in healthy young adults (47). Such shortcomings may underlie the very low training increases in aerobic fitness often found, for example, in cardiac rehabilitation programs (48). Thus, the present work points toward a reconsideration of the way in which exercise intensity is prescribed to improve cardiovascular health and suggests that the use of the exercise intensity domain schema, which can offer a more uniform metabolic disruption across individuals, represents a more effective tool to achieve this goal. In fact, we have recently highlighted how participants who are on the lower and upper range of the fitness level spectrum are more likely to have the metabolic disturbance of a given activity to be underestimated and overestimated, respectively, when exercise prescription is based on activities that are considered to be of moderate or heavy intensity (15).

Experimental considerations. The main objective of this study was to compare training responses to domain-specific exercise intensities. The training program design was developed to emulate common aerobic exercise training and physical activity guidelines, which typically recommend the accumulation of 150 min of "moderate-to-vigorous" activity weekly. Importantly, these guidelines are composed for those who are not currently meeting these targets and would benefit from improvements in their aerobic fitness. From a practical perspective, these findings can help inform exercise training strategies for these cohorts but do not necessarily apply to those who are competitively training more than 5 times a week where periodization, recovery, and multi-intensity sessions are important considerations. Except for SIT, all exercise training groups were work-matched to a MOD equivalent, but other normalizing approaches exist including training impulse (TRIMP) or training stress score (TSS). We favored our approach because TRIMP is based on HR responses that are known to vary daily even for the same exercise load. In addition, TSS is calculated using only one threshold (i.e., functional threshold power as the upper boundary of the heavy-intensity domain), which, itself, carries limitations that reduce accuracy. Some issues with other approaches to establish training loads have been discussed elsewhere (49). Given that a single-intensity per-group approach was used, work matching at the individual level was deemed to be more appropriate as we were able to consider the position of both thresholds (i.e., θ_{LT} and MMSS).

Although new laboratory-based methods exist to identify with high accuracy the boundaries demarcating the intensity domains in a relatively time- and cost-efficient way (50,51), it is acknowledged that determining θ_{LT} and MMSS is challenging in nonlaboratory settings. However, our findings demonstrate that some attempt to determine exercise intensity domains would be helpful to inform exercise prescription in situations where limited weekly sessions are performed and improvements in aerobic fitness need to be maximized. In this regard, future work should explore how a combination of simple tools that require no equipment (e.g., rating of perceived

exertion, talk-test, etc.) or the use of relatively easy to access wearable technologies (e.g., heart rate variability, near-infrared spectroscopy, and/or respiratory rate–derived thresholds, etc.) could be used to gain a close approximation of intensity domain-based prescription for practical settings.

CONCLUSIONS

The findings of this study highlight the critical importance of exercise intensity domain-based prescription to control the metabolic disturbance and deliver a homogenous stimulus across individuals. It demonstrates that the exercise intensity domain within which the activity is performed is key to determine changes in $\dot{V}O_{2max}$ as well as in submaximal thresholds following an exercise training program, and that there may be a minimal intensity of exercise needed to produce these changes. Moreover, it shows that HIIT performed within the severe-intensity domain was the most effective at producing improvements across all measured variables. We suggest that current methods commonly used for exercise intensity prescription are no longer justifiable and that the difference in metabolic disturbance produced by the intensity domains needs to be considered to maximize the chances of eliciting positive adaptations to training. A paradigm shift is needed for developing updated physical activity and exercise prescription methods and guidelines that incorporate exercise-intensity domains.

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