Twelve weeks of sprint interval training increases maximal cardiac output

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ABSTRACT

The improved maximal oxygen uptake ($\dot{V}O_{2max}$) after traditional moderate intensity continuous training (MICT) is generally attributed to increased maximal cardiac output ($\dot{Q}_{max}$). Sprint interval training (SIT) increases $\dot{V}O_{2max}$ similar to MICT despite a lower training volume, but the effect on $\dot{Q}_{max}$ is unclear. **Purpose:** To determine the effect of ~30 sessions of SIT over 12 weeks on $\dot{Q}_{max}$ and its association with the change in $\dot{V}O_{2max}$. **Methods:** 15 healthy untrained adults [6 males, 9 females; 21±2 y (mean±SD)] performed a SIT protocol involving 3x20-s 'all-out' cycling bouts (581±221 W) within a 10-min period. $\dot{V}O_{2max}$ was determined using a ramp test to exhaustion. $\dot{Q}_{max}$ was determined using inert gas rebreathing over a 2-min period at a workload that elicited $\dot{V}O_{2max}$ during the measurement period. All variables were assessed twice at baseline following familiarization and again after 2, 6 and 12 weeks of SIT. Reproducibility of $\dot{V}O_{2max}$ and $\dot{Q}_{max}$, determined using the baseline measures and expressed as a coefficient of variation, were 5.8 and 4.7%, respectively. **Results:** $\dot{V}O_{2max}$ increased from 2.65±0.85 at baseline to 2.85±9.6, 3.03±1.1 and 3.18±1.1 L/min after 2, 6 and 12 weeks, respectively ($p<0.001$ for all). $\dot{Q}_{max}$ increased from 17.2±3.8 at baseline to 18.1±4.6 L/min after 12 weeks ($p=0.04$) but was not different after 2 (17.2±4.2; $p=0.96$) or 6 weeks (17.9±4.4; $p=0.14$). The changes in $\dot{V}O_{2max}$ and $\dot{Q}_{max}$ from baseline to 12 weeks were positively correlated ($r^2=0.46$, $p=0.005$). Secondary exploratory analyses revealed that males increased $\dot{Q}_{max}$ after 6 and 12 weeks, but there was no change in females. **Conclusion:** The increase in $\dot{V}O_{2max}$ after 12 weeks of SIT is associated with an increase in $\dot{Q}_{max}$, and there may be sex-specific differences in this regard.

Key words: Exercise, maximal oxygen uptake, stroke volume, time trial performance.

INTRODUCTION

Maximal oxygen uptake ($\dot{V}O_{2max}$) reflects the peak integrated capacity of the body to transport and utilize oxygen. As defined by the Fick principle, $\dot{V}O_{2max}$ is determined by the product of maximal cardiac output ($\dot{Q}_{max}$) and maximal arterio-venous oxygen difference (a-vO_{2diff}). In healthy individuals exercising at sea level, $\dot{V}O_{2max}$ is believed to be primarily limited by $\dot{Q}_{max}$ (1), and it is generally accepted that training-induced improvements in $\dot{V}O_{2max}$ are primarily owing to an increased $\dot{Q}_{max}$ (2). Supporting evidence for this assertion includes a recent 6-week training study that found a strong correlation between increases in $\dot{V}O_{2max}$ and $\dot{Q}_{max}$ as measured non-invasively using inert gas rebreathing ($r = 0.84$, $p < 0.0001$) (3). Increases in $\dot{Q}_{max}$ are believed to be mediated by increased stroke volume (SV) through the Frank-Starling mechanism (1, 4, 5).

Sprint interval training (SIT) involves brief repeated bursts of very intense exercise, typically performed using 'near-maximal' to 'all out' efforts that exceed the absolute workload that elicits $\dot{V}O_{2max}$, separated by short periods of recovery (6, 7). SIT is a potent stimulus for inducing physiological remodelling and can increase $\dot{V}O_{2max}$ similar to MICT despite a lower training volume (8). For example, Gillen et al. (9) compared responses to a SIT protocol involving three 20-s all-out cycling sprints, set within a 10-min session including warm-up, recovery and cool-down, as compared to a MICT protocol involving 50-min of continuous cycling. Twelve weeks of either SIT or MICT similarly increased $\dot{V}O_{2max}$ by a mean of 19%, or ~2 metabolic equivalents (METs), despite the SIT protocol involving a five-fold lower training volume and time commitment (9). The mechanistic basis for SIT-induced increases in $\dot{V}O_{2max}$ are unclear, and there are limited and equivocal data regarding potential changes in $\dot{Q}_{max}$.

Several studies have reported no change in $\dot{Q}_{max}$ after 4-6 weeks of SIT despite an increase in $\dot{V}O_{2max}$ of ~10% or ~1-MET (10, 11). $\dot{Q}_{max}$ in these studies was determined by either acetylene

non-rebreathing (10) or an inert gas rebreathing-corrected photoplethysmography technique (11). Given the observed lack of change in $\dot{Q}_{max}$, and based on the Fick principle, the increase in $\dot{V}O_{2max}$ in these studies was attributed to an increase in maximal a-vO_{2diff}. Rapid increases in skeletal muscle mitochondrial and capillary density after short-term SIT (12, 13) could potentially facilitate an increase in oxygen extraction, although direct measures of oxygen extraction have not been performed following SIT. Conversely, one study found that 12 sessions of a protocol involving ten 1-min bouts performed at a workload that elicited $\dot{V}O_{2max}$ increased $\dot{Q}_{max}$ and $\dot{V}O_{2max}$ in active women after 4 weeks (14). The effect of SIT on $\dot{Q}_{max}$, including the time course for changes and potential relationship with changes in $\dot{V}O_{2max}$, remains unclear.

The primary purpose of the present study was to determine the time course for changes in $\dot{V}O_{2max}$ and $\dot{Q}_{max}$ over 12 weeks of SIT, performed three times per week, in untrained but healthy young adults. It was hypothesized that $\dot{V}O_{2max}$ would increase after 2, 6 and 12 weeks of training, and this increase in $\dot{V}O_{2max}$ would be associated with a corresponding increase in $\dot{Q}_{max}$ after 6 and 12 weeks. In addition to the primary variables of interest, we assessed potential changes in exercise capacity using a time trial (TT).

METHODS

Participants

Sample size was determined based on the estimated change in $\dot{Q}_{max}$ and the standard deviation reported in a previous study (10). Thirteen participants were required to detect a change at an alpha level of 0.05 with 80% power. To preserve power in the event of participant withdrawal, a total of 15 healthy untrained adults were recruited (6 males and 9 females; 21 ± 2 y; 172±11 cm; 72±20 kg; mean ± SD). The classification as untrained was based on a self-reported engagement

<1 h per week of moderate to vigorous physical activity (Canadian Society for Exercise Physiology Get Active Questionnaire). The study procedures were approved by the Hamilton Integrated Research Ethics Board, and all participants provided written informed consent prior to their participation.

Preliminary Testing

Participants initially reported to the laboratory for a familiarization visit, and subsequently on four different occasions to facilitate baseline testing sessions, each separated by at least 48 h. $\dot{V}O_{2max}$ and $\dot{Q}_{max}$ were determined during the first and third baseline sessions. Submaximal exercise responses and TT performance were determined during the second and fourth baseline sessions. Baseline values are reported as the mean of the two baseline measurements.

Measurements

Maximal oxygen uptake. $\dot{V}O_{2max}$ was determined using a ramp incremental exercise test to exhaustion on a cycle ergometer (Lode Excalibur Sport V 2.0, Groningen, The Netherlands). A metabolic cart with an on-line gas collection system (Quark CPET metabolic cart, COSMED, Italy) acquired $\dot{V}O_2$ and carbon dioxide production throughout the test, and heart rate (HR) was monitored continuously with a HR monitor (Polar A3, Finland). The test began with a 3-min warm up at 50 W, after which the resistance was increased by 1 W every 2 s until volitional exhaustion or the participant was unable to maintain a pedal cadence above 60 rpm. $\dot{V}O_{2max}$ was recorded as the highest $\dot{V}O_2$ achieved over a 30-s period. For all tests, participants achieved at least two of the following criteria: 1) maximal perceived exertion; 2) HR within 10 beats per min of age-predicted maximum (220 - age); 3) RER > 1.1; and 4) a plateau in $\dot{V}O_2$.

Maximal cardiac output. $\dot{Q}_{max}$ was assessed non-invasively using inert gas rebreathing (Innocor, Innovision, Odense, Denmark), ~20 min following the $\dot{V}O_{2max}$ test. Following a 1-min warm up at 50 W, participants cycled at 90% of the peak power output attained during the $\dot{V}O_{2max}$ test (90% W_{peak}). After 2 min of cycling at 90% W_{peak}, participants began breathing a mixture of 3 gases (94% oxygen, 5% nitrous oxide, 1% sulfur hexafluoride) from a closed-circuit rebreathing bag (Innocor, Innovision) for 5-6 breaths. The volume of the rebreathing bag was automatically customized to each participant using the tidal volume measured during the 2 min prior to the rebreathing to ensure unrestricted ventilation. To calculate cardiac output ($\dot{Q}$), the Innocor measures the disappearance rate of nitrous oxide (a blood soluble gas that diffuses into the pulmonary blood stream) relative to sulfur hexafluoride (a blood insoluble gas) over the course of the rebreathing period using photoacoustic gas analyzers. Pilot testing (n=5) confirmed that cycling at 90% W_{peak} elicited oxygen uptake levels equivalent to $\dot{V}O_{2max}$ within 2 min in all participants, including for the subsequent measurement period that was assumed to correspond to $\dot{Q}_{max}$. HR was monitored continuously (Polar). SV_{max} was calculated as $SV_{max} = \dot{Q}_{max}/HR_{max}$. Maximal a-$vO_{2diff}$ was calculated from the Fick equation as a-$vO_{2diff} = \dot{V}O_{2max}/\dot{Q}_{max}$.

Submaximal exercise responses. Participants cycled for 15 min at a workload corresponding to ~65% of their pre-training $\dot{V}O_{2max}$ on an ergometer (Lode Excalibur Sport). HR was monitored using a HR monitor (Polar). $\dot{V}O_2$ was measured during the first 8 min of exercise to ensure steady state was achieved. At min 12, $\dot{Q}$ was assessed using the inert gas rebreathing procedure described above. SV was calculated as $SV = \dot{Q}/HR$.

Time trial. Participants completed a 2 kJ/kg body weight TT on a cycle ergometer (Lode Excalibur Sport), ~15 min following the submaximal exercise responses. Participants were instructed to complete the TT as quickly as possible. The only feedback provided was the

proportion of work completed, presented on a computer monitor for the duration of the TT. HR (Polar) was recorded throughout, in addition to the measurement of time to completion and mean power.

Training intervention

Training was performed on a cycle ergometer (Velotron, RacerMate, Seattle, WA) and involved a 2-min warm-up (50 W), 3 x 20-s 'all-out' sprints interspersed with 2 min of unloaded cycling, and a 3-min cool-down (50 W). Participants were permitted to listen to music, and all training sessions were supervised. Aside from the supervised exercise sessions, participants were instructed to make no changes to their physical activity habits throughout the duration of the study. Two training sessions during each of weeks 3 and 7 were devoted to testing to assess responses to 2 and 6 weeks of training, respectively. The final post-training measurements of $\dot{V}O_{2max}$ and $\dot{Q}_{max}$ were performed 72 h after the last training bout, followed 48 h later by the TT. All submaximal exercise comparisons were made at the same absolute workload. Due to a technical error related to absolute workload setting, submaximal exercise responses were regrettably not determined as originally intended after 12 weeks of training, which yielded invalid data for comparative purposes.

Statistical analysis

Within group differences were assessed using one-way repeated measures analysis of variance (ANOVA) comparing each follow-up time point (2, 6 and 12 weeks) to baseline. Between group differences for SV_{submax} and SV_{max} were assessed using two-way repeated measures ANOVA comparing SV_{submax} to SV_{max} at baseline, 2 and 6 weeks. An exploratory analysis was also performed to probe for a potential sex-based difference in the Q_{max} response to training, using a

two-way ANOVA with sex (male vs. female) as the between factor and time (2, 6 and 12 weeks vs. baseline) as the within factor. Dunnett's Test was used to adjust for multiple comparisons. Partial eta-squared (η^2_p) effect sizes are reported. Relationships between variables were assessed using simple linear regression. Method error reproducibility for $\dot{V}O_{2max}$, $\dot{Q}_{max}$ and TT performance was calculated as the coefficient of variation (CV) based on the two baseline sessions for each measure, using the method described by Sale (15), i.e., CV = (root mean square deviation / mean) * 100. A paired sample t-test was used to assess differences between the baseline sessions. ANOVA and regression analyses were performed using GraphPad Prism 6 with significance set to $p < 0.05$. All results are presented as means ± SD.

RESULTS

Training

Mean power output for the three, 20 s sprint bouts, averaged across all training sessions, was 581±221 W. Mean HR across all sprint bouts was 92±3% HR_{max}, and mean HR averaged over the 10-min period of each training session was 80±5% HR_{max}.

$\dot{V}O_{2max}$ and $\dot{Q}_{max}$

$\dot{V}O_{2max}$ determined for the two baseline visits was 2.62 and 2.68 L/min, respectively, which yielded a CV of 5.8%, with no difference between time points (p=0.4). The corresponding determinations for $\dot{Q}_{max}$ were 17.0±3.7 and 17.5±4.0 L/min, respectively, with a CV of 4.7% and no difference between time points (p=0.2). The slope of the $\dot{V}O_{2max}$-$\dot{Q}_{max}$ relationship at baseline was 4.1±0.5 L/L (p<0.001). Absolute $\dot{V}O_{2max}$ increased from 2.65±0.85 (mean of the two baseline visits) to 2.85±9.6 (p=0.006), 3.03±1.1 (p=0.003) and 3.18±1.1 L/min (p<0.001) after 2, 6 and 12 weeks of SIT, respectively (η^2_p=0.62; Figure 1A). Expressed in relative terms, $\dot{V}O_{2max}$

increased from 37.0±7.3 (mean of the two baseline visits) to 39.7±7.9, 42.0±8.6 and 44.3±8.7 ml/kg/min ($p<0.001$ for all, $\eta^2_p=0.67$). $\dot{Q}_{max}$ increased from 17.2±3.8 to 18.1±4.6 L/min after 12 weeks ($p=0.04$, $\eta^2_p=0.31$) but was not different after 2 (17.2±4.2, $p=0.96$) or 6 weeks (17.9±4.4, $p=0.14$) (Figure 1B). The calculated max a-vO_{2diff} was 152±21 at baseline and increased to 163±21 ($p<0.001$), 166±23 ($p=0.002$) and 174±23 ml O_2/L blood ($p<0.001$) after 2, 6 and 12 weeks of SIT ($\eta^2_p=0.52$).

The exploratory analysis revealed an interaction effect such that the increase in $\dot{Q}_{max}$ was different between men and women ($p<0.001$, $\eta^2_p=0.45$). Male participants increased $\dot{Q}_{max}$ after 6 and 12 weeks compared to baseline ($p<0.001$ for both), whereas the female participants did not increase $\dot{Q}_{max}$ at any time point (Figure 2A). The increase in $\dot{Q}_{max}$ was greater than the method error CV in 5/6 males and 2/9 females (Figure 2B). $\dot{V}O_{2max}$ increased after 2 ($p=0.004$), 6 and 12 weeks ($p<0.001$ for both) in males and after 6 ($p=0.03$) and 12 weeks ($p<0.001$) in females compared to baseline; however, there was an interaction effect such that the males increased to a greater extent ($p<0.001$, $\eta^2_p=0.38$).

There were positive correlations between the change from baseline to 12 weeks of training in $\dot{Q}_{max}$ and $\dot{V}O_{2max}$ ($r^2=0.46$, $p=0.005$; Figure 3A), and the change in max a-vO_{2diff} and $\dot{V}O_{2max}$ ($r^2=0.33$, $p=0.03$; Figure 3B).

HR_{max} and SV_{max}

HR_{max} increased from 185±9 to 189±9 bpm after 12 weeks of SIT ($p=0.006$) but was not different after 2 (185±8) or 6 weeks (186±9) ($p=0.9$ for both). Calculated SV_{max} increased from 97±21 ml at baseline to 103±26 ml after 6 weeks ($p=0.04$) but was not different after 2 (98±25,

p=0.66) or 12 weeks (101±28, p=0.14). The change in SV_{max} from baseline to 12 weeks of SIT was positively correlated with the change in $\dot{Q}_{max}$ over this period (r^2=0.78, p<0.001).

Submaximal exercise responses

The cardiac responses during submaximal exercise are summarized in Table 1 (n=13). HR_{submax} decreased after 2 and 6 weeks compared to baseline, but $\dot{Q}_{submax}$ and SV_{submax} were not different. Averaged across baseline, 2-, and 6-weeks, SV_{submax} was 94±21 ml and SV_{max} was 99±24 ml, and two-way repeated measures ANOVA revealed that these were not significantly different (p=0.06).

TT performance

A subset of participants performed the TT performance test twice at baseline (n=8); the time was 18:13±3:18 min:s and 17:18±3:03 min:s, respectively, which yielded a CV of 4.2%, with performance being ~5% faster on the second effort (p=0.01). The two baseline measures were averaged, and the data combined with the remaining six participants who only performed one baseline performance test. One participant was unable to perform the final TT owing to scheduling constraints and was excluded from the analysis (n=14). TT performance improved from 17:26±4:02 min:s at baseline to 15:51±3:53 and 14:44±3:56 after 2 and 12 weeks of SIT, respectively (p<0.001 for both, η^2_p=0.53); the value at 6 weeks was not different from baseline (16:21±4:16 min:s, p=0.14). There were no sex-based differences in TT performance (p=0.38, η^2_p=0.08).

DISCUSSION

The primary novel finding of this study was that 12 weeks of SIT increased $\dot{Q}_{max}$ in previously untrained young adults, and changes in $\dot{Q}_{max}$ were positively correlated with changes in $\dot{V}O_{2max}$

over this period. The calculated change in maximal a-vO_{2diff} was also positively correlated with the change in $\dot{V}O_{2max}$. Exploratory secondary analyses suggested a potential sex-based difference, with $\dot{Q}_{max}$ increasing in males after 6 and 12 weeks, but not in females.

The 20% increase in $\dot{V}O_{2max}$ after 12 weeks of SIT is consistent with a previous investigation from our laboratory that reported a 19% increase after the same SIT protocol, as well as 12 weeks of MICT (9). MacPherson and colleagues found that 6 weeks of SIT, involving 3 weekly sessions of 4-6 x 30-s of 'all-out' running on a manually driven treadmill, separated by 4-min of recovery, increased $\dot{V}O_{2max}$ to the same extent as 6 weeks of MICT (~10% increase for both) (10). $\dot{Q}_{max}$ in that study, however, was only increased after MICT. Two other investigations (11, 16) similarly reported no change in $\dot{Q}_{max}$ after 4 weeks of a SIT protocol involving 8 x 20-s at 170% $\dot{V}O_{2max}$ with 10-s recoveries on a cycle ergometer, although $\dot{V}O_{2max}$ was only increased in one study (11). The lack of change in $\dot{Q}_{max}$ despite increased $\dot{V}O_{2max}$ after 4-6 weeks of SIT is suggestive of an increased maximum a-vO_{2diff}, based on the Fick principle. Consistent with the previous studies, we observed no measurable change in $\dot{Q}_{max}$ after 2 and 6 weeks. The present study is the first to demonstrate a SIT-induced increase in $\dot{Q}_{max}$ after 12 weeks of training, which was positively correlated with the increase in $\dot{V}O_{2max}$ over this period. The increase in calculated maximal a-vO_{2diff} was also positively correlated with increased $\dot{V}O_{2max}$ after 12 weeks, which suggests both central and peripheral factors may contribute to the improvement in $\dot{V}O_{2max}$ after 12 weeks of SIT.

$\dot{Q}_{max}$ is commonly assessed non-invasively using inert gas rebreathing because it is strongly correlated with the gold standard direct Fick (r=0.95) and thermodilution (r=0.94) methods (17, 18). The CV of $\dot{Q}_{max}$ assessment in the literature is generally reported to be in the range of 7-11% (17, 19). Measurements of $\dot{Q}_{max}$ are typically performed by having participants indicate when

they are ~30-s from exhaustion during a ramp exercise test, at which point the inert gas rebreathing is initiated and $\dot{Q}_{max}$ measured. As part of pilot testing for the present study, we determined that 2-min of cycling at 90% W_{peak} elicited $\dot{V}O_{2max}$. Inert gas rebreathing measurements performed after this 2-min period were subsequently assumed to correspond to $\dot{Q}_{max}$, given that $\dot{V}O_{2max}$ was attained. The CV for the $\dot{Q}_{max}$ assessment protocol used in our study was 4.7%, which may have improved our ability to detect changes in $\dot{Q}_{max}$ following SIT. Although $\dot{Q}_{max}$ assessment using inert gas rebreathing is strongly correlated to gold-standard measures (17, 18), a limitation of this method is that after a period of ~5 seconds, the blood containing nitrous oxide is recirculated into the pulmonary system. This phenomenon may reduce the diffusion gradient of nitrous oxide from the rebreathing bag into the pulmonary blood stream, resulting in an underestimation of $\dot{Q}_{max}$. This limitation is attenuated, however, by the short duration of the rebreathing period, which spans 5-6 breaths or ~8 s.

Our exploratory analysis suggests a potential sex-based difference in the $\dot{Q}_{max}$ response to SIT, with an increase in males but no change in females. Only 2/9 female participants demonstrated an increase in $\dot{Q}_{max}$ that was greater than the method error CV, where 5/6 males increased. Relative exercise heart rate was not different between males and females during the SIT intervention (i.e., 77% and 82% HR_{max}, respectively, p=0.13), suggesting the differential $\dot{Q}_{max}$ response was not owing to a difference in training intensity. A recent systematic review and meta-analysis suggested a potential impact of sex on left ventricular cardiac adaptations to exercise training, and concluded there were markedly blunted and distinct moderating factors of key left ventricular functional adaptations in females compared with males (20). The present, limited analyses suggest there may also be an attenuated cardiac response in females compared to males following low volume SIT. Recent research suggests that although $\dot{V}O_{2max}$ and $\dot{Q}_{max}$ are

unaffected by menstrual cycle phase (luteal vs. follicular) and oral contraceptive phase (active vs. inactive) (21, 22), oral contraceptive use may blunt the increase in $\dot{V}O_{2max}$ and $\dot{Q}_{max}$ in response to SIT in active females (14). The majority of females in our study were not taking oral contraceptives (5/9), but the relatively low participant number precludes a meaningful assessment of the potential influence of this factor. The previous study (14) also involved a larger total volume of exercise as compared to the present work, and unlike most studies that have examined the effect of SIT on $\dot{Q}_{max}$ (10, 11), the protocol did not involve 'all out' efforts. Additional studies are warranted to probe the potential for sex-based differences in the $\dot{Q}_{max}$ response to SIT, as well as the impact of initial training state, specific exercise intervention, and oral contraceptive use.

It is generally accepted that at exercise intensities above ~40% of $\dot{V}O_{2max}$, the increase in SV plateaus and SV_{max} is achieved (23); however, others have contested that SV continues to increase progressively until $\dot{V}O_{2max}$, suggesting SV_{submax} at or above ~40% VO_{2max} may not accurately depict SV_{max}, and therefore not result in accurate calculation of $\dot{Q}_{max}$, in all individuals (24). We investigated the effect of SIT on both calculated SV_{max} and SV_{submax} and found that they were not statistically different (p=0.06). While previous research found a SIT-induced improvement in SV_{submax} at exercise intensities $\leq$ 50% $\dot{V}O_{2max}$ (25, 26), the observed increase in SV_{submax} after 6 weeks of training in our study was not statistically significant. Interestingly, the mean calculated increases in SV_{submax} and SV_{max} after 6 weeks of training in our study were similar (4.8±10 vs 5.3±7 ml, respectively), despite only the increase in SV_{max} being statistically significant. This disconnect may be owing to higher day-to-day variability in SV_{submax} compared to SV_{max} (CV=7.4 vs. 4.7%, respectively), possibly related to the fact that SV at submaximal workloads may plateau in some, but not all individuals (24). We also measured a small but

significant increase in HR_{max} after 12 weeks of training; however, this increase was not associated with the change in Q_{max}.

SIT improved TT performance by ~9% after 2 weeks, which is consistent with other 2-week studies in untrained individuals (27–29). While TT performance was numerically improved after 6 weeks of training compared to baseline, the difference was not statistically significant. TT performance was nonetheless significantly improved by ~16% compared to baseline after 12 weeks of training. To our knowledge, this is the longest duration study to evaluate the effect of low volume SIT on exercise performance in untrained individuals and the only study assessing the timeline of improvement. In addition to increased $\dot{V}O_{2max}$, the mechanisms responsible for the SIT-induced improvement in performance could be related to enhanced skeletal muscle oxidative capacity (27, 28) and potentially an improved exercise economy (30). While the mechanisms are likely different, SIT has also been shown to improve exercise performance in highly endurance-trained athletes (31–33). Participants improved their TT performance by ~5% from the first to second baseline assessment. Hopkins (34) proposed that a change of 1.5-2 times greater than the CV should be considered a training-induced effect. While performance was not the major focus of the present study, the improvement after 2 weeks compared to baseline was 2.2 times greater than the CV (i.e., 9.2% versus 4.2%, respectively). This is suggestive of a genuine training effect in addition to any potential residual learning effect.

CONCLUSION

In summary, we report an increase in $\dot{Q}_{max}$ after 12 weeks of SIT in previously untrained participants, which was positively correlated with the increase in $\dot{V}O_{2max}$ over this period. Exploratory analyses suggested potential sex-based differences in the $\dot{Q}_{max}$ training response, with increases observed in males after 6 and 12 weeks of SIT compared to pre-training but not in

309 females. Additional work is warranted to probe the potential for sex-based differences in the
310 $\dot{Q}_{max}$ response to SIT. More invasive studies are also needed to advance our understanding of the
311 mechanistic basis for SIT-induced changes in $\dot{Q}_{max}$ and $\dot{V}O_{2max}$, including measurements of total
312 blood volume and direct Fick measures of the a-vO_2diff during maximal exercise.

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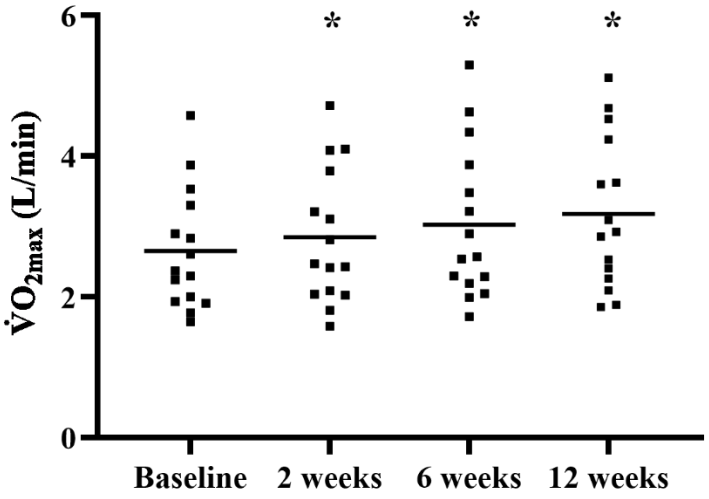
FIGURE CAPTIONS

Figure 1: $\dot{V}O_{2max}$ (A) and $\dot{Q}_{max}$ (B) before training and after 2, 6 and 12 weeks of SIT. Mean (lines) and individual (squares) data are presented (n=15). * $p<0.05$ vs. baseline.

A)



B)

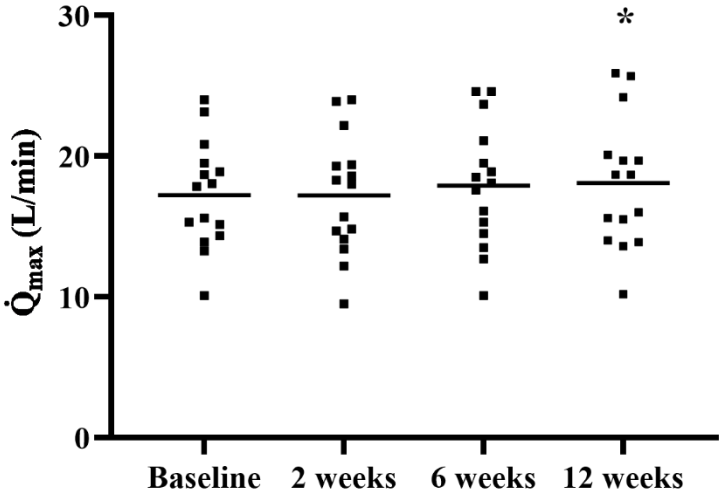
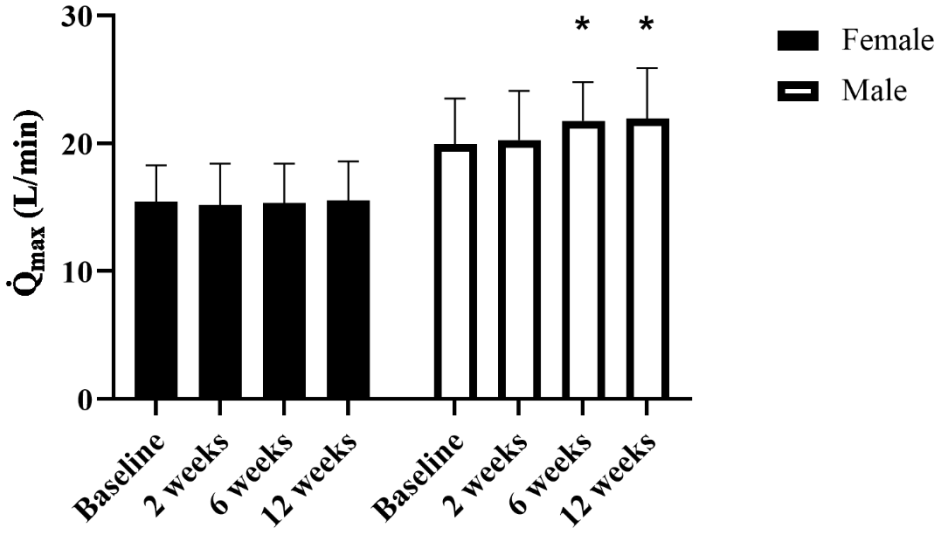


Figure 2: $\dot{Q}_{max}$ before training and after 2, 6 and 12 weeks of SIT in male and female participants (A) and the relative change in $\dot{Q}_{max}$ after 12 weeks of SIT for males (open squares) and females (closed dots) as compared to the CV (shaded area). * $p<0.05$ vs. baseline.

A)



B)

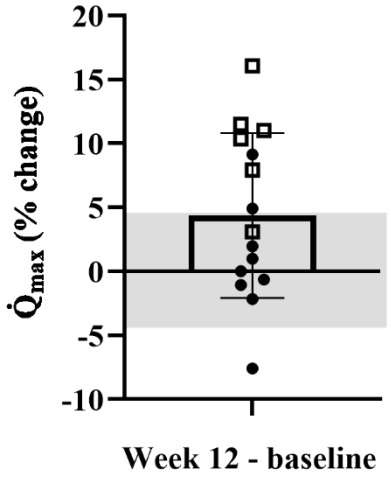
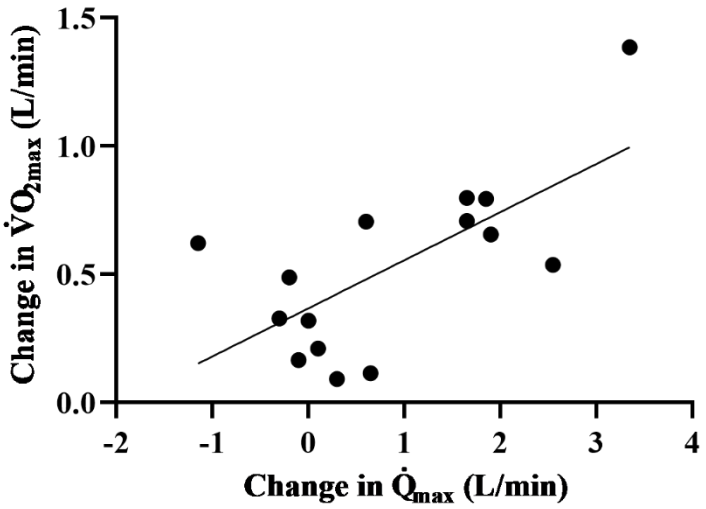


Figure 3: Correlation between the change in $\dot{Q}_{max}$ and $\dot{V}O_{2max}$ (A) and max a-vO_{2diff} and $\dot{V}O_{2max}$ (B) from baseline to 12 weeks of SIT. * $p<0.05$.

A)



B)

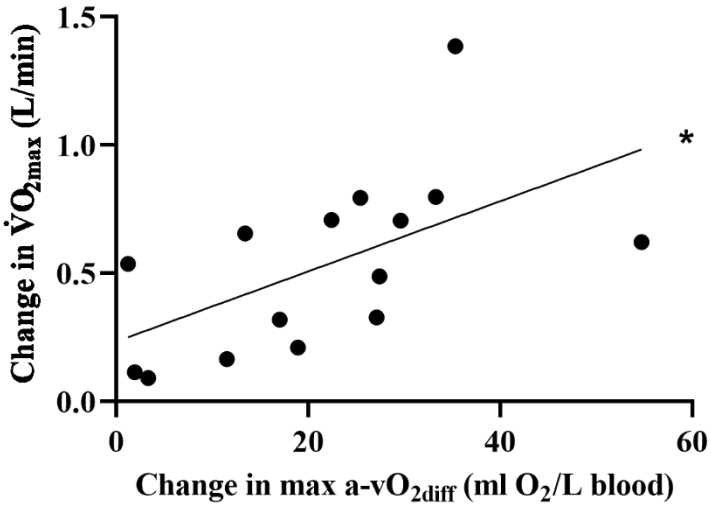


Table 1: Submaximal exercise responses at baseline and after 2 and 6 weeks of SIT.

	Baseline	2 weeks	6 weeks
$\dot{V}O_2$ (L/min)	1.9 ± 0.4	1.8 ± 0.3 (p=0.06)	1.8 ± 0.4 (p=0.35)
$\dot{Q}$ (L/min)	14.0 ± 2.9	13.7 ± 3.0 (p=0.44)	13.8 ± 2.6 (p=0.82)
SV (ml)	92 ± 21	93 ± 22 (p=0.62)	96 ± 22 (p=0.19)
HR (bpm)	154 ± 14	148 ± 10 (p=0.02)	146 ± 15 (p=0.02)

Data are mean ± SD (n=13). P values denote comparisons vs baseline.