Received: 15 May 2023 | Revised: 9 July 2023 | Accepted: 8 August 2023
DOI: 10.1111/sms.14470

ORIGINAL ARTICLE

WILEY

Aerobic high-intensity intervals improve $\dot{V}O_{2max}$ more than supramaximal sprint intervals in females, similar to males

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Funding information
The Research Counsil of Norway

Abstract

Introduction: Maximal oxygen uptake ($\dot{V}O_{2max}$) is a pivotal factor for aerobic endurance performance. Recently, aerobic high-intensity interval training (HIIT) was documented to be superior to sprint interval training (SIT) in improving $\dot{V}O_{2max}$ in well-trained males. However, as mounting evidence suggests that physiological responses to training are sex-dependent, examining the effects of HIIT versus SIT on $\dot{V}O_{2max}$, anaerobic capacity, and endurance performance in females is warranted.

Methods: We randomized 81 aerobically well-trained females (22 ± 2 years, 51.8 ± 3.6 mL·kg^{-1}·min^{-1} $\dot{V}O_{2max}$), training three times weekly for 8 weeks, to well-established protocols: (1) HIIT 4 × 4 min at ~95% of maximal aerobic speed (MAS), with 3 min active recovery (2) SIT 8 × 20 s at ~150% of MAS, with 10 s passive recovery (3) SIT 10 × 30 s at ~175% of MAS, with 3.5 min active recovery.

Results: Only HIIT 4 × 4 min increased $\dot{V}O_{2max}$ (7.3 ± 3.1%), different from both SIT groups (all $p < 0.001$). Anaerobic capacity (maximal accumulated oxygen deficit) increased following SIT 8 × 20 s (6.5 ± 10.5%, $p < 0.05$), SIT 10 × 30 s (14.4 ± 13.7%, $p < 0.05$; different from HIIT 4 × 4 min, $p < 0.05$). SIT 10 × 30 s resulted in eight training-induced injuries, different from no injuries following HIIT 4 × 4 min and SIT 8 × 20 s ($p < 0.001$). All groups improved long-distance (3000-meter) and sprint (300-meter) running performance (all $p < 0.001$). SIT protocols improved sprint performance more than HIIT 4 × 4 min ($p < 0.05$). Compared to previous male results, no increase in $\dot{V}O_{2max}$ following SIT 8 × 20 s ($p < 0.01$), and a higher injury rate for SIT 10 × 30 s ($p < 0.001$), were evident.

Conclusions: In aerobically well-trained women, HIIT is superior to SIT in increasing $\dot{V}O_{2max}$ while all-out treadmill running SIT is potentially more harmful.

KEYWORDS
aerobic power, anaerobic capacity, hamstring strain, HIIT, maximal oxygen uptake, muscular strain, sex-differences, SIT

1 | INTRODUCTION

Maximal oxygen uptake ($\dot{V}O_{2max}$) is widely acknowledged as a key physiological factor for endurance events involving large muscle mass, such as middle- and long-distance running.[1,2] The last decades a myriad of training programs has emerged to effectively improve $\dot{V}O_{2max}$, with high-intensity intervals typically advocated to induce the largest increases.[3,4] However, what may be the optimal interval format to improve $\dot{V}O_{2max}$ is unclear, and sex-specific empirical evidence of training-induced responses in females is scarce.

Interval training may be classified as aerobic high-intensity interval training (HIIT) or supramaximal sprint interval training (SIT). HIIT typically targets high *aerobic* intensity of about ≥90% of $\dot{V}O_{2max,}$ corresponding to ~95% of maximal aerobic speed (MAS), while SIT targets high *overall* intensity of about ≥150% of MAS.[4,5] Because of sluggish $\dot{V}O_2$-kinetics, and that intensity is not maximal, the duration of HIIT needs to be adequately long for overloading of oxygen transporting organs to occur. Thus, HIIT is commonly conducted with an interval length of 3–5 min.[3] Albeit, this may also be achieved with shorter intervals if recovery periods are also short (e.g., 15 s), preventing a significant decline in $\dot{V}O_2$.[6] In contrast to HIIT, the intervals' length during SIT is forced to be ≤1 min because of the rapid fatigue at this intensity.[7] The length of recovery periods between intervals impacts the SIT protocols physiological attributes and typically vary from a few seconds (e.g., 10 s) to several min (e.g., 4 min).[4,5] Short recovery periods during SIT facilitate a very high taxation of both aerobic power and anaerobic capacity, albeit only for a very short time due to the rapid fatigue.[8,9] Longer recovery periods during SIT facilitate a higher rate of anaerobic metabolism in every single interval, and larger accumulated volume of work during the sprint intervals compared to SIT with short breaks.[8]

In a recent study comparing HIIT with SIT in aerobically well-trained males (baseline $\dot{V}O_{2max}$ of ~63 mL kg^{-1} min^{-1}) it was documented that HIIT resulted in a superior improvement in $\dot{V}O_{2max}$, likely explained by the greater overload on oxygen transport during HIIT.[8] In line with this notion, there is no evidence that an extreme engagement of anaerobic processes, such as during SIT, is necessary to train the aerobic system. Yet, somewhat surprising, moderately trained females (baseline $\dot{V}O_{2max}$ of 35 mL kg^{-1} min^{-1}) have been demonstrated to exhibit similar improvements in $\dot{V}O_{2max}$ following HIIT and SIT with long recovery periods.[10] Furthermore, SIT may be superior to HIIT in improving other factors than $\dot{V}O_{2max}$ contributing to running performance, as the anaerobic system is typically highly taxed during SIT.[11] Additionally, both HIIT and SIT may improve running economy,[3,5] while lactate threshold (LT) is typically unaltered in already well-trained subjects.[12] However, physiological differences between the sexes are evident for both $\dot{V}O_{2max}$ and anaerobic capacity,[2,13] and possibly running economy.[14] There are also some reports that training-induced adaptations of these factors may differ between the sexes,[15,16] albeit this is not a universal finding.[17,18] Compared with males, females have smaller lungs, higher mechanical work of breathing, lower hemoglobin concentration, greater proportion of oxidative slow-twitch type I skeletal muscle fibers, higher capillary density, and greater fatigue resistance.[19] All these factors may potentially affect training-induced responses to HIIT and SIT and alter the reliance on aerobic versus anaerobic energy systems. In addition to sex, it is also crucial to consider the individuals' training status, since training responses may be greater in less trained individuals, and potentially easier influenced by other aspects (e.g., technique) than physiology.

Recognizing the importance of $\dot{V}O_{2max}$, and that HIIT and SIT, two popular training formats to improve this key physiological factor, appears to only have been contrasted in aerobically well-trained men,[8,20] a study investigating what may be the better interval format for $\dot{V}O_{2max}$ improvements in aerobically well-trained females (i.e., mean baseline $\dot{V}O_{2max} > 50$ mL kg^{-1} min^{-1}) is warranted. In addition, running economy and LT also impact long-distance performance and should be investigated concomitantly.[2] It is also of interest to examine effects on anaerobic capacity and the energy systems' implications for performance, as anaerobic sources may account for ~10% of the energy during long-distance performance (i.e., 3000-meter running).[1]

Thus, the aim of the current study was to compare HIIT and SIT in aerobically well-trained females and contrast results to the recent findings in aerobically well-trained males following identical training protocols.[8] Specifically, we compared one commonly applied HIIT protocol with two frequently used SIT protocols: (1) HIIT 4×4 min; 4×4 min at ~95% of MAS interspersed by 3 min active recovery, (2) SIT 8×20 s; 8×20 s at ~150% of MAS interspersed by 10 s passive recovery, (3) SIT 10×30 s; 10×30 s at ~175% of MAS interspersed by 3.5 min active recovery. We hypothesized that (1) HIIT 4×4 min would improve $\dot{V}O_{2max}$ and long-distance endurance performance more than both SIT protocols, (2) both SIT protocols would improve anaerobic capacity and sprint endurance performance more than HIIT 4×4 min, (3) no differences between HIIT and SIT would be apparent for running economy and LT as a percentage of $\dot{V}O_{2max}$.

2 | METHODS

2.1 | Subjects

Eighty-one healthy non-smoking females volunteered to participate in the present study and were randomized by non-stratified block randomization into three training groups: HIIT 4×4 min, SIT 8×20 s, or SIT 10×30 s (Figure 1). The subjects were physically active university students who regularly exercised, either at their own or in organized sports. To ensure homogeneity, specialized runners and male subjects were not invited to participate. However, our group recently conducted a study on males of similar training status as the females included in the present study.[8] The present and previous study applied similar methods, and our results therefore include analyses between the sexes. We did not control for oral contraceptive or menstrual cycle phase, as $\dot{V}O_{2max}$ and exercise performance do normally not vary within these phases.[21] Inclusion criteria were whole-body endurance training at least once per week, a $\dot{V}O_{2max} \geq 40\,mL\,kg^{-1}\,min^{-1}$, and being accustomed to treadmill running. Participants with ≤80% compliance to training were excluded. Participants were informed with a written consent, and the Institutional Review Board of the Norwegian University of Science and Technology approved the protocol. The study was carried out in accordance with the Declaration of Helsinki.

2.2 | Descriptives

Age, height, and body mass for the subjects randomized to the respective groups were 23 ± 3 years, 169 ± 6 cm, and 64.7 ± 7.9 kg for HIIT 4 × 4 min (*n* = 23); 22 ± 2 years, 170 ± 8 cm, and 65.1 ± 7.4 kg for SIT 8 × 20 s (*n* = 26); 22 ± 2 years, 168 ± 6 cm, and 62.9 ± 8.6 kg for SIT 10 × 30 s (*n* = 27).

2.3 | Study timeline

The participants met twice in a laboratory for metabolic testing and once at an indoor track and field arena for time trials, all within 2 weeks of the intervention period. They had at least 1 day of rest preceding each test, and at least 2 days (64–72 h) of rest between training and post-test. All tests were conducted in the same order pre- and post-intervention. All training interventions were conducted three times weekly for 8 weeks.

2.4 | Testing procedures

Testing procedures have been described previously.[8] A motorized treadmill (Woodway PPS 55 Sport, Germany) was set at 3° inclination during all metabolic testing. Therefore, all relationships between pulmonary oxygen uptake ($\dot{V}O_2$) and velocity in the present study (e.g., running economy, LT, MAS) were collected at this incline. For comparison with males, hemoglobin concentration of capillary blood was measured during rest using Hemocue Hb-801 (Angelholm, Sweden). The subjects washed and warmed their hands in lukewarm water before the procedure, and the first three drops of blood was wiped away. Three samples were then taken consecutively, and the mean of these three was regarded as the hemoglobin concentration.

2.4.1 | Test day 1 ($\dot{V}O_{2max}$, running economy, and lactate threshold)

Ten minutes of warm-up preceded 5-min stages of running to determine LT. At least three stages had to be completed, and the velocity was increased by 1 km h^{-1} between each stage. $\dot{V}O_2$ and heart rate (HR) were continuously measured using a Cortex Metamax II (Cortex Biophysik GmbH, Leipzig, Germany) and a HR

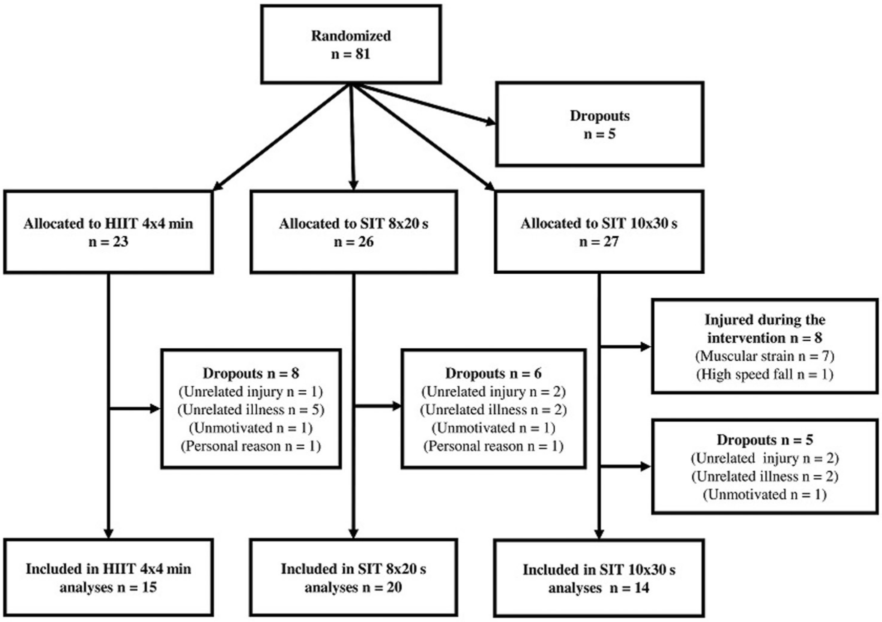

FIGURE 1 Flowchart of the study. HIIT 4 × 4 min, 4 × 4 min running at ~95% of maximal aerobic speed (MAS) interspersed by 3 min active recovery; SIT 8 × 20 s, 8 × 20 s exhaustive running at ~150% of MAS interspersed by 10 s passive recovery; SIT 10 × 30 s, 10 × 30 s maximal running (average of ~175% MAS) interspersed by 3.5 min active recovery.

monitor (Polar Electro Oy, Finland), respectively. Following warm-up and each stage, blood was drawn from a fingertip and analyzed with a Biosen C-line lactate analyzer (EKF-diagnostic GmbH, Germany). LT was defined as the $\dot{V}O_2$, HR, or velocity associated with a rise in blood lactate concentration ($[\text{la}^-]_b$) of 1.5 mM above the lowest measured $[\text{la}^-]_b$.[3] Measurement of running economy was implemented in the LT protocol, and running economy was assessed as the average $\dot{V}O_2$ during the last 30 s at the 7 km h^{-1} 5-min stage. A $[\text{la}^-]_b$ sample was analyzed to assure that 7 km h^{-1} was below LT, and visual inspection to control that steady state had been achieved was conducted. After the running economy and LT procedure, the participants walked for approximately 5 min before conducting an incremental $\dot{V}O_{2\text{max}}$-test. The starting intensity of the $\dot{V}O_{2\text{max}}$-test was ≥LT, and the velocity was thereafter increased by 1 km h^{-1} every minute until exhaustion. Strong verbal encouragement was given during the last minutes, and $[\text{la}^-]_b$ was measured within 1 min after termination of the test. The highest 30-s average $\dot{V}O_2$ was defined as $\dot{V}O_{2\text{max}}$, and the highest recorded HR was regarded as HR_{max}. Maximal O_2 pulse was calculated as $\dot{V}O_{2\text{max}}$ divided by HR_{max}. A leveling off in $\dot{V}O_2$ despite increased power output or minute ventilation, combined with either a $[\text{la}^-]_b$ above 8 mM and/or a respiratory exchange ratio above 1.10 were used as $\dot{V}O_{2\text{max}}$ criteria.[22] Additionally, $\dot{V}O_{2\text{max}}$ values from the incremental protocol were verified the second test day. If either 30-s average $\dot{V}O_2$ and/or HR reached higher values during the second test day, these values were used as $\dot{V}O_{2\text{max}}$ and/or HR_{max}.

Since $\dot{V}O_2$ (volume per unit of time) does not increase proportional to body mass (volume) but with an exponent of approximately 0.75,[14] $\dot{V}O_{2(\text{max})}$ should be scaled with body mass raised to the power of 0.75 (mL kg$^{-0.75}$ min^{-1}). Furthermore, both heart stroke volume and anaerobic capacity (volumes), as well as O_2 pulse (volume per unit of time divided by frequency), should be scaled with body mass raised to the power of 1. Correct scaling ratios are especially important when comparing subjects with large differences in body mass, for example, men and women.

2.4.2 | Test day 2 (anaerobic capacity and $\dot{V}O_{2\text{max}}$ verification)

Anaerobic capacity was defined as maximal accumulated oxygen deficit (MAOD) and measured according to the simplified procedure nr. 3 in Medbø et al.[23] By using three or more submaximal measurements from test day 1 and a Y-intercept of 5.0 mL kg^{-1} min^{-1} (representing standing resting metabolism), a linear regression was established between $\dot{V}O_2$ and velocity. Using this regression, MAS was defined as the speed corresponding to the participants $\dot{V}O_{2\text{max}}$.

Test day 2 started with a warm-up at ~70% of HR_{max} for 15 min. Two ~10 s sprints were included at the intensity of the upcoming supramaximal bout, toward the end of the warm-up procedure. Subsequently, participants rested for 10 min and a $[\text{la}^-]_b$ measurement was administered to ensure resting $[\text{la}^-]_b$ of ±1 mM prior to the supramaximal bout. The intensity of the supramaximal bout was 120 ± 10% of MAS, and the target duration was 2–3 min.[23] The participants were not aware of the target duration, and they were instructed to run until absolute exhaustion. The test was repeated on a separate day if the target duration was missed by ±15 s. Data from the supramaximal bout were used to verify $\dot{V}O_{2\text{max}}$ from test day 1 and calculate MAOD.

The total accumulated oxygen cost (in VO_2) of the supramaximal bout, which is a theoretical value, was estimated by extrapolating the linear relationship between submaximal $\dot{V}O_2$ and velocity to the supramaximal intensity of the test, giving an estimated oxygen cost per unit of time equivalent to 120 ± 10% of $\dot{V}O_{2\text{max}}$. The true accumulated VO_2 during this bout was measured, and MAOD was then calculated as:

$$\text{Estimated total oxygen cost} - \text{measured accumulated } VO_2 \tag{1}$$

In addition, since the relationship between $\dot{V}O_2$ and velocity probably is slightly curvilinear, total accumulated oxygen cost was also calculated with the velocity during the supramaximal bout (minus 7 km h^{-1}) raised to the power of 1.05, based on Equation (1) in Hill and Vingren[24]:

$$O_2 \text{ cost} = O_2 \text{ cost at } 7\,\text{km h}^{-1} + \left[a\left(\text{velocity} - 7\,\text{km h}^{-1}\right)^{1.05}\right] \tag{2}$$

We did not adjust this calculation for stored oxygen bound to myoglobin and hemoglobin, which constitutes about 9% of the MAOD.[23]

2.4.3 | Test day 3 (long-distance and sprint running performance)

The performance tests were conducted indoor on a banked 200-meter track and field and timed manually using two separate stopwatches, administered by two researchers. Individual low-intensity warm-up of 10 min, including 2–4 acceleration runs, followed by ~7 min of rest, preceded the 300-meter sprint running time trial. The 300-meter test was conducted as an individual start and rounded to the nearest tenth of a second. After the sprint test, 20 min of rest, a second low-intensity warm-up of 10 min duration, and 5 min of rest preceded the 3000-meter long-distance running time trial. The long-distance test was performed as mass starts with up to 10 participants in each of the groups, and the measured time rounded to the nearest second. The participants received verbal encouragement during both time trials. The instructions and duration of the warm-ups were standardized between pre- and post-test, but the intensity and number of acceleration runs (before 300-meter) were not controlled within subjects.

2.5 | Training interventions

The interventions in the present study are identical to a recent study.[8] The participants were encouraged to continue as usual with most physical activities (e.g., soccer, handball, and hiking), but instructed to refrain from other high-intensity endurance training. The treadmills (Gymleco LTX200, Sweden) were set at ~3° inclination and the warm-up consisted of running at ~70% of HR_{max} for 10 min for all three interventions. For the SIT groups only, the warm-up included 2–3 supramaximal bouts of 10–15 s near the interval training intensity. Intensity was controlled and determined by HR during HIIT 4×4 min and performance/fatigue during the SIT-protocols, albeit the intensity of each protocol is consequently referred to as a percentage of MAS for comparative reasons.

2.5.1 | HIIT 4×4 min

This group ran four intervals of 4 min duration at ~95% of MAS, interspersed by 3 min of active recovery at an intensity corresponding to ~70% of HR_{max}. The intensity was continuously controlled by HR measurements. If 90%–95% of HR_{max} was not reached within 3 min of each interval, the intensity was adjusted to reach the target HR in the following session. This protocol does not elicit exhaustion. The HIIT 4×4 min protocol lasted 38 min in total, including a cooldown of 3 min at an intensity corresponding to 70% of HR_{max}.

2.5.2 | SIT 8×20 s

This group ran approximately eight intervals of 20 s duration at ~150% of MAS, interspersed by 10 s of passive recovery. The participants' task was to accomplish as many intervals as possible, and they had one-to-one encouragement during every interval. The intensity was set with an aim to exhaust the participants during interval eight or nine. If the subject managed to complete a ninth interval, the intensity was increased in the upcoming session. With this design, absolute exhaustion is reached during the last 20-s interval. The SIT 8×20 s protocol lasted ~25 min in total, including the warm-up, and a 10-min cooldown at an intensity corresponding to 70% of HR_{max}. Although this protocol was originally reported to be carried out at ~170% of MAS,[4] we chose an intensity of ~150% of MAS for the first training sessions because a pilot in our laboratory revealed too rapid exhaustion when applying 170% of MAS (i.e., during interval 4, 5, or 6). From the second session and onwards, the intensity was adjusted based on number of intervals completed during the previous training session.

2.5.3 | SIT 10×30 s

This group ran 10 intervals of 30 s duration, interspersed by active recovery periods of 3.5 min at ≤70% of HR_{max}. In this protocol, every single interval is exhaustive (i.e., "all-out"). This necessitates a drop in intensity throughout a session because the fatiguing intensity of a maximal sprint cannot be repeated for 10 consecutive bouts. The average interval intensity was ~175% of MAS, and the starting workload in the first training session was approximately 120% of each participants' average workload during the 300-meter performance pretraining. From the second session and onwards, the intensity in every interval was adjusted based on performance during the previous interval and previous training session. All participants had one-to-one follow-up during every single interval, ensuring that all intervals led to exhaustion. The SIT 10×30 s protocol lasted 49 min in total, including 3 min of cooldown at an intensity corresponding to ≤70% of HR_{max}.

2.6 | Statistical analysis

The statistical analyses were conducted with IBM SPSS Statistics 29 software (IBM Corp., USA). Figures were created using GraphPad Prism 9 (GraphPad Software, USA). $p < 0.05$ were used as the level of significance in all cases. Two-way ANOVAs were used to investigate differences between groups, and Tukey's WSD post-hoc analysis was used when appropriate. $\dot{V}O_{2max}$, time trial, and MAOD data were tested for normality using QQ-plots and the Shapiro–Wilk test, and the assumptions of normal distribution were met. Results are presented as mean ± SD in text and tables and mean ± SE in figures. The relationship between performance and physiological factors was analyzed using Pearson correlation. Injury rates between groups was analyzed using Fisher's exact test.

3 | RESULTS

3.1 | Body mass, compliance, and training progression

The SIT 10×30 s group reduced body mass by 1.1 ± 2.0 kg ($p = 0.049$) from pre- to post-test, while neither HIIT 4×4 min nor SIT 8×20 s did alter body mass. The change in body mass was not different between groups. The mean number of intervals in the SIT 8×20 s group were 8.0 ± 0.3. The subjects included in the analyses completed 23 ± 1 (HIIT 4×4 min), 22 ± 2 (SIT 8×20 s), and 22 ± 1 (SIT 10×30 s) training sessions, and all 49 participants included in the final analyses completed at least 20 training sessions according to their respective protocol. At 3° inclination, mean improvement of interval velocity during the intervention were 1.2 ± 0.3 km h^{-1} for HIIT 4×4 min, 1.4 ± 0.6 km h^{-1} for SIT 8×20 s, and 1.4 ± 0.5 km h^{-1} for SIT 10×30 s.

3.2 | Summary of results from males

The results from the present study are compared to a study of males.[8] The males' results are briefly summarized as: $\dot{V}O_{2max}$ improved more ($p < 0.001$) following HIIT 4×4 min (6.5 ± 2.4%, $p < 0.001$) compared to SIT 8×20 s (3.3 ± 2.4%, $p < 0.001$) and SIT 10×30 s (ns). MAOD improved more ($p < 0.05$) following SIT 8×20 s (11.6 ± 15.6, $p < 0.05$) compared to HIIT 4×4 min (ns) only, and not ($p > 0.05$) compared to SIT 10×30 s (ns). Long-distance running performance improved more ($p < 0.05$) following HIIT 4×4 min (5.9 ± 3.2%, $p < 0.001$) compared to SIT 10×30 s (2.2 ± 2.2%, $p < 0.05$), but not compared to SIT 8×20 s (4.1 ± 3.7%, $p < 0.01$). Sprint running performance improved following SIT 8×20 s (4.4 ± 2.0%, $p < 0.01$) and SIT 10×30 s (3.3 ± 2.8%, $p < 0.01$), but not HIIT 4×4 min (ns), with no differences between groups ($p > 0.05$). No training-induced injuries were observed in any protocol.

3.3 | Injuries and dropouts

There were more injuries during SIT 10×30 s compared to both HIIT 4×4 min, SIT 8×20 s and male SIT 10×30 s ($p < 0.001$). The SIT 10×30 s induced six hamstring strains, one calf strain, and one high-speed fall. All eight injuries made the respective subjects unable to continue training within 7 days of the injury. Other reasons for not meeting the ≥80% compliance criteria or failure to complete the testing are listed in Figure 1 as dropouts.

3.4 | Maximal oxygen uptake, oxygen pulse, and hemoglobin concentration in blood

Only HIIT 4×4 min exhibited within-group increase in $\dot{V}O_{2max}$ (7.3 ± 3.1%, $p < 0.001$) and O_2 pulse (8.4 ± 3.7%, $p < 0.001$), and these increases were larger ($p < 0.001$) compared to both SIT protocols (Table 1 and Figure 2). In SIT 8×20 s, no training-induced change in $\dot{V}O_{2max}$ and O_2 pulse were observed, contrary to males ($p < 0.01$, Table 1 and Figure 2). Hemoglobin concentration in blood was 13.7 ± 1.4 g dl^{-1} (HIIT 4×4 min), 13.9 ± 1.0 g dl^{-1} (SIT 8×20 s), and 13.5 ± 0.4 g dl^{-1} (SIT 10×30 s), respectively. No differences in hemoglobin concentration were apparent between the groups, but they were all significantly lower than in males ($p < 0.01$). Of individual responses, three subjects in each SIT group improved $\dot{V}O_{2max}$ by 3%–6%, while all subjects in HIIT 4×4 min improved $\dot{V}O_{2max}$ by 3% or more.

3.5 | Maximal accumulated oxygen deficit

Both SIT 8×20 s (6.5 ± 10.5%) and SIT 10×30 s (14.4 ± 13.7%) exhibited within-group increases in MAOD ($p < 0.05$, Table 2), while there was a tendency for improved MAOD within the HIIT 4×4 min group (4.4 ± 9.3%) with the linear ($p = 0.06$) and curvilinear ($p = 0.07$) calculation method. At baseline, SIT 10×30 s had lower MAOD compared to HIIT 4×4 min ($p < 0.05$), and SIT 10×30 s increased MAOD (mL kg^{-1}) more than HIIT 4×4 min ($p < 0.05$) from pre- to post-test, yet only with the linear calculation model. Females exhibited reduced MAOD compared to males at baseline ($p < 0.001$) and the training-induced change in MAOD (L) for SIT 8×20 s was lower compared to males ($p < 0.05$, Table 2). No other sex-differences in MAOD were observed (Table 2).

3.6 | Sprint and long-distance running performance

All groups exhibited within-group improvement in both 300-meter (3.1%–6.2%) and 3000-meter (all 4.5%) running performance (all $p < 0.001$, Figure 3). The performance on 300-meter improved more following both SIT protocols compared to HIIT 4×4 min ($p < 0.05$, Figure 3), albeit this was reduced to a tendency ($p = 0.054$ and 0.056 vs. SIT 8×20 s and SIT 10×30 s, respectively) when covaried for 300 m performance pre-training. The improvement in both sprint ($p < 0.01$) and long-distance performance ($p < 0.05$) following SIT 10×30 s were larger compared to males (Figure 3).

TABLE 1 Data from pre- and post-test of aerobic endurance factors.

	HIIT 4×4 min ($n=15$)		SIT 8×20 s ($n=20$)		SIT 10×30 s ($n=14$)		Group effects		
	Pre	Post	Pre	Post	Pre	Post	HIIT 4×4 min vs. SIT 8×20 s	HIIT 4×4 min vs. SIT 10×30 s	Reduced improvement compared to males in Hov et al.,[8] 2023
HR_{max} (beats min^{-1})	195 ± 10	193 ± 10*	199 ± 8	199 ± 8	195 ± 9	194 ± 9	ns	ns	ns
Maximal oxygen pulse									
mL $beat^{-1}$	17.2 ± 1.4	18.5 ± 1.2***	17.0 ± 2.2	17.2 ± 2.2	17.1 ± 2.7	17.3 ± 2.3	$p=0.002$	$p=0.004$	SIT 8×20 s, $p=0.004$
mL kg^{-1} $beat^{-1}$	0.271 ± 0.023	0.294 ± 0.023***	0.269 ± 0.021	0.272 ± 0.023	0.267 ± 0.021	0.271 ± 0.017	$p<0.001$	$p<0.001$	SIT 8×20 s, $p=0.037$
MAS (km h^{-1})	10.3 ± 1.1	11.4 ± 1.1***	11.0 ± 1.4	11.4 ± 1.6***	10.8 ± 1.2	10.9 ± 1.1	$p=0.003$	$p<0.001$	ns
Running economy									
L min^{-1}	2.42 ± 0.31	2.31 ± 0.24*	2.27 ± 0.28	2.21 ± 0.27**	2.31 ± 0.37	2.28 ± 0.34	ns	ns	ns
mL kg^{-1} min^{-1}	37.6 ± 3.3	36.9 ± 3.1	35.9 ± 3.0	35.1 ± 3.1**	35.5 ± 2.6	35.2 ± 2.2	ns	ns	ns
mL $kg^{-0.75}$ min^{-1}	105.9 ± 9.4	103.9 ± 8.7	101.0 ± 8.4	98.8 ± 8.5**	100.6 ± 8.6	99.5 ± 6.9	ns	ns	ns
HR (beats · min^{-1})	169 ± 14	162 ± 15**	170 ± 14	166 ± 15	167 ± 12	166 ± 9	ns	$p=0.033$	ns
$[La^-]_b$ (mM)	2.2 ± 0.7	1.6 ± 0.6***	2.0 ± 1.1	1.9 ± 1.0	2.2 ± 1.3	2.1 ± 1.0	p = 0.024	$p=0.039$	ns
Lactate Threshold									
L min^{-1}	2.62 ± 0.26	2.71 ± 0.18*	2.61 ± 0.33	2.65 ± 0.35	2.59 ± 0.38	2.58 ± 0.28	ns	ns	ns
mL kg^{-1} min^{-1}	41.3 ± 3.5	43.1 ± 3.6**	41.4 ± 3.7	42.1 ± 4.7	39.9 ± 3.5	40.6 ± 3.5	ns	ns	ns
mL $kg^{-0.75}$ min^{-1}	116.6 ± 9.3	121.2 ± 8.6**	116.7 ± 10.2	118.4 ± 12.5	113.1 ± 9.8	114.5 ± 8.9	ns	ns	ns
% $\dot{V}O_{2max}$	78 ± 4	76 ± 3	77 ± 5	78 ± 6	77 ± 5	78 ± 6	ns	ns	ns
Velocity (km h^{-1})	7.9 ± 0.7	8.5 ± 0.9***	8.3 ± 1.0	8.6 ± 1.2**	8.0 ± 0.9	8.3 ± 0.8	ns	$p=0.043$	ns
$[La^-]_b$ (mM)	3.0 ± 0.4	2.8 ± 0.4*	3.0 ± 0.8	3.0 ± 0.6	3.1 ± 0.7	3.2 ± 0.6	ns	$p=0.017$	ns

Note: Data are presented as mean ± SD. HIIT 4×4 min, 4×4 min running at ~95% of maximal aerobic speed (MAS) interspersed by 3 min active recovery; SIT 8×20 s, 8×20 s exhaustive running at ~150% of MAS interspersed by 10 s passive recovery; SIT 10×30 s, 10×30 s maximal running (average of ~175% MAS) interspersed by 3.5 min active recovery; ns, not significant. Significant change from pre- to post-test within group (*$p<0.05$, **$p<0.01$, ***$p<0.001$).

Abbreviations: HR, heart rate; $[La^-]_b$, blood lactate concentration.

3.7 | Noteworthy correlations

Post training, 3000-meter performance was associated with $\dot{V}O_{2max}$ ($r = -0.66$, $p < 0.001$), running economy ($r = 0.39$, $p < 0.01$), velocity at LT ($r = -0.86$, $p < 0.001$), and MAS ($r = -0.77$, $p < 0.001$) across all groups. 300-meter performance post training was associated with $\dot{V}O_{2max}$ ($r = -0.42$, $p < 0.01$), velocity at LT ($r = -0.36$, $p < 0.01$), MAOD ($r = -0.32$, $p < 0.05$), and MAS ($r = -0.34$, $p < 0.05$) across all groups. The changes in running performance following training did not correlate with changes in any other variable.

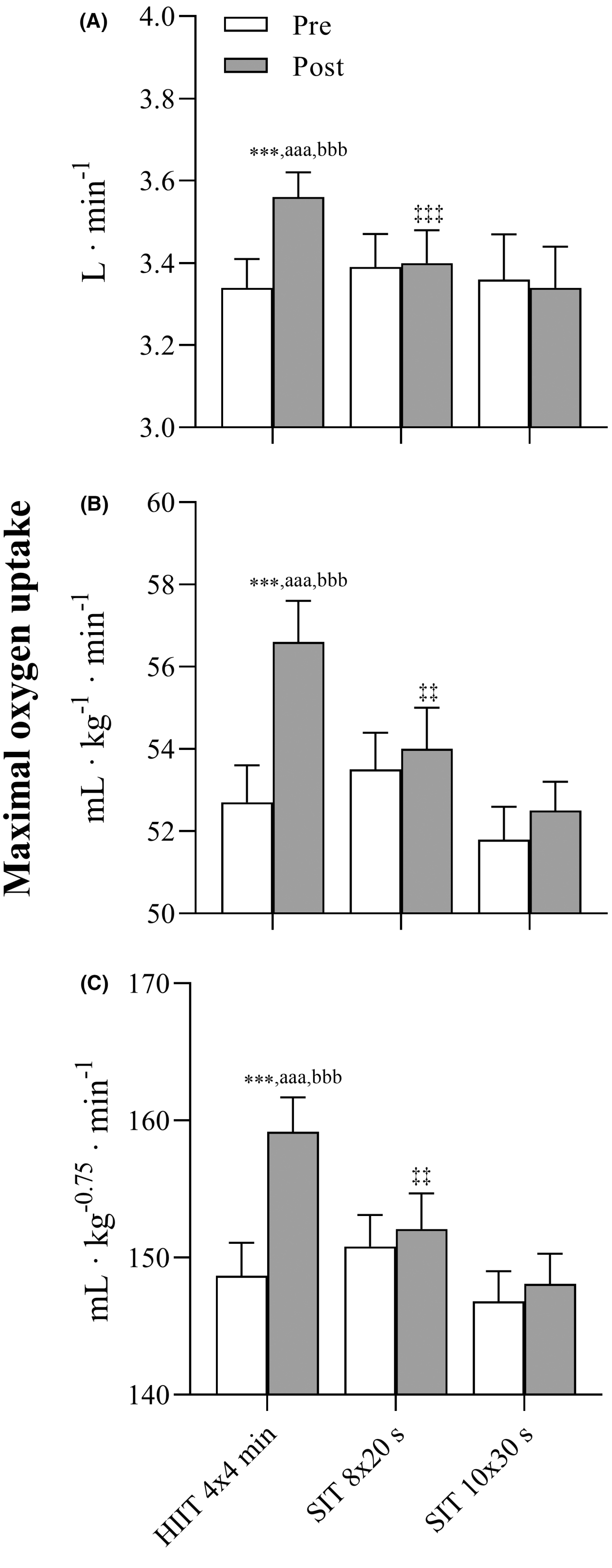

FIGURE 2 Maximal oxygen uptake at pre- and post-test given as L min^{-1} (A), mL kg^{-1} min^{-1} (B) and mL kg$^{-0.75}$ min^{-1} (C). Data are presented as mean ± SEM. HIIT 4 × 4 min, 4 × 4 min running at ~95% of maximal aerobic speed (MAS) interspersed by 3 min active recovery; SIT 8 × 20 s, 8 × 20 s exhaustive running at ~150% of MAS interspersed by 10 s passive recovery; SIT 10 × 30 s, 10 × 30 s maximal running (average of ~175% MAS) interspersed by 3.5 min active recovery. Significant different change from pre- to post-test; within group (***$p < 0.001$), compared to SIT 10 × 30 s (aaa $p < 0.001$), compared to SIT 8 × 20 s (bbb $p < 0.001$). Significantly lesser improvement compared to male subjects within the same protocol in Hov et al.,[8] 2023 ($^{‡‡}p < 0.01$, $^{‡‡‡}p < 0.001$).

4 | DISCUSSION

Recently it was documented that HIIT was superior to SIT for improving $\dot{V}O_{2max}$ in males. However, physiological responses to training may be sex-dependent and training-induced effects must be investigated in females to provide good exercise prescriptions. Thus, in the current study, we examined the impact of HIIT and SIT on $\dot{V}O_{2max}$ in females, along with effects on anaerobic capacity, and sprint- and long-distance endurance performance. Main findings were that (1) HIIT 4 × 4 min improved $\dot{V}O_{2max}$ more than both SIT with short (8 × 20 s) and long (10 × 30 s) recovery periods, (2) Neither of the SIT protocols did improve $\dot{V}O_{2max}$, (3) ~30% of the women randomized to SIT 10 × 30 s was injured during training, while no injuries occurred during HIIT 4 × 4 min or SIT 8 × 20 s, (4) Compared with males of similar training status,[8] we observed no effect of SIT 8 × 20 s on $\dot{V}O_{2max}$, a higher risk of injury during SIT 10 × 30 s, and a larger improvement in sprint and long-distance time trial following SIT 10 × 30 s in females, (5) Anaerobic capacity increased following both SIT protocols and tended to improve following HIIT 4 × 4 min, with no conclusive differences between groups, (6) All groups improved sprint- and long-distance running performance, but SIT protocols improved the former more than HIIT 4 × 4 min. Taken together with previous observations in males our findings strengthens the assumption that HIIT is the interval format of choice for improving $\dot{V}O_{2max}$, SIT protocols have a greater potential to improve anaerobic capacity, and running performance may be improved by both HIIT and SIT. However, of importance, caution may be warranted for aerobically well-trained females when

TABLE 2 Data from pre- and post-test of anaerobic capacity.

	HIIT 4 × 4 min ($n = 15$)		SIT × 20 s ($n = 20$)		SIT 10 × 30 s ($n = 14$)		Group effects		
	Pre	Post	Pre	Post	Pre	Post	HIIT 4 × 4 min vs SIT 8 × 20 s	HIIT 4 × 4 min vs SIT 10 × 30 s	Reduced improvement compared to males in Hov et al.,[8] 2023
MAOD									
L	4.44 ± 0.81	4.64 ± 0.87	4.34 ± 0.73	4.52 ± 0.63*	4.06 ± 0.80	4.46 ± 0.66**	ns	ns	SIT 8 × 20 s, $p = 0.016$
$\mathrm{mL\,kg^{-1}}$	70.7 ± 12.7	73.6 ± 13.1	67.8 ± 8.5	71.6 ± 7.5*	62.2 ± 9.2§	70.6 ± 9.2**	ns	$p = 0.050$	ns
L (curvilinear)	4.81 ± 0.87	5.03 ± 0.89	4.71 ± 0.80	4.97 ± 0.71*	4.45 ± 0.86	4.86 ± 0.75*	ns	ns	ns
$\mathrm{mL\,kg^{-1}}$ (curvilinear)	76.1 ± 13.9	79.9 ± 15.5	73.9 ± 9.1	78.4 ± 7.2*	68.2 ± 10.2	77.0 ± 11.9**	ns	ns	ns
Velocity									
% MAS	123 ± 6	119 ± 5*	122 ± 8	124 ± 9**	119 ± 8	123 ± 8*	$p = 0.002$	$p < 0.001$	ns
$\mathrm{km\,h^{-1}}$	12.9 ± 1.0	13.9 ± 1.1***	13.4 ± 0.9	14.3 ± 1.2***	13.0 ± 1.1	13.7 ± 1.2***	ns	ns	SIT 10 × 30 s, $p = 0.004$
TTE (seconds)	148 ± 23	143 ± 28	140 ± 17	133 ± 16	140 ± 18	144 ± 21	ns	ns	ns

Note: Data are presented as mean ± SD. HIIT 4×4 min, 4×4 min running at ~95% of maximal aerobic speed (MAS) interspersed by 3 min active recovery; SIT 8×20 s, 8×20 s exhaustive running at ~150% of MAS interspersed by 10 s passive recovery; SIT 10×30 s, 10×30 s maximal running (average of ~175% MAS) interspersed by 3.5 min active recovery; Curvilinear, calculation of MAOD based on the curvilinear relationship between oxygen cost and running velocity established by Hill & Vingren;[24] ns, not significant. Significant different change from pre- to post-test; within group ($^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$). Significantly different from 4×4 min at baseline ($^{\S}p < 0.05$).

Abbreviation: MAOD, maximal accumulated oxygen deficit; TTE, time to exhaustion.

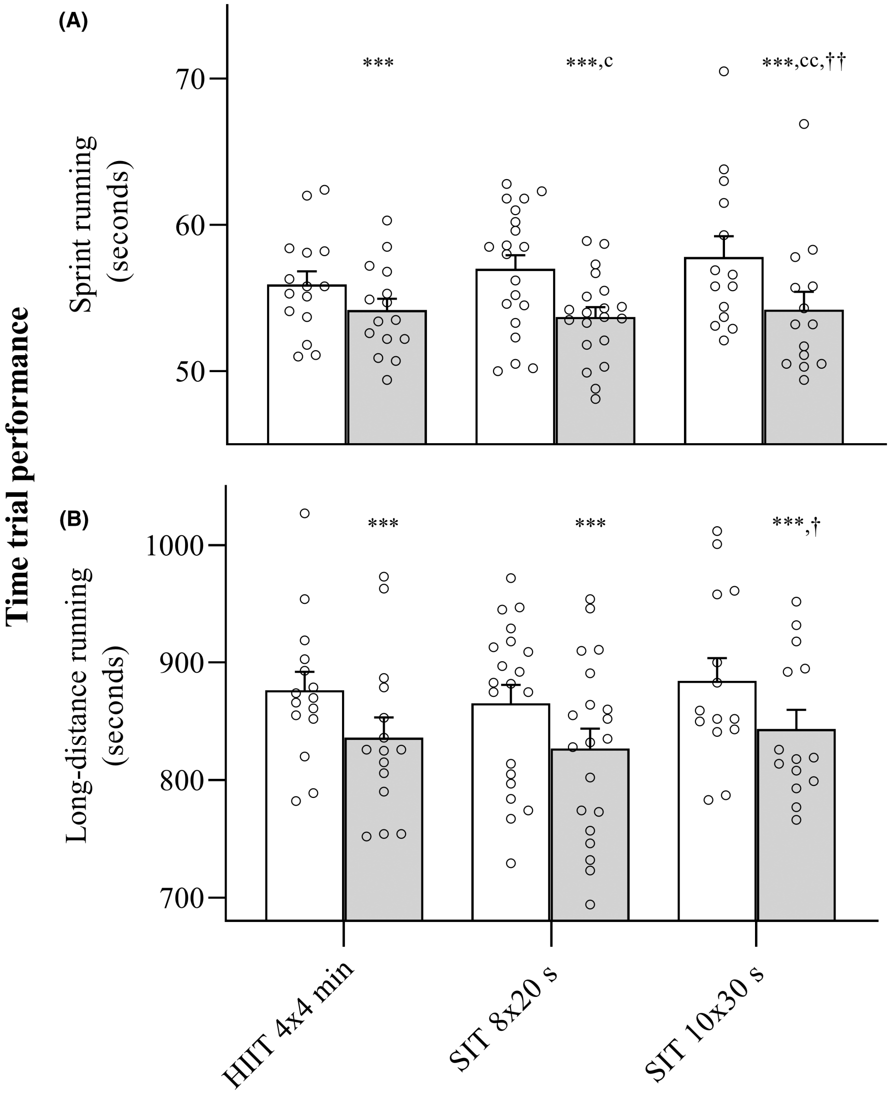

FIGURE 3 Sprint running performance (A) and long-distance running performance (B) at pre- and post-test. Data are presented as mean ± SEM. HIIT 4×4 min, 4×4 min running at ~95% of maximal aerobic speed (MAS) interspersed by 3 min active recovery; SIT 8×20 s, 8×20 s exhaustive running at ~150% of MAS interspersed by 10 s passive recovery; SIT 10×30 s, 10×30 s maximal running (average of ~175% MAS) interspersed by 3.5 min active recovery. Significant different change from pre- to post-test; within group (***$p < 0.001$), compared to HIIT 4×4 min (c $p < 0.05$, cc $p < 0.01$). Significantly larger improvement compared to male subjects within the same protocol in Hov et al.,[8] 2023 ($^{\dagger}p < 0.05$, $^{\dagger\dagger}p < 0.01$).

considering applying a treadmill running protocol like SIT 10×30 s because of the high risk of injuries.

4.1 | Interval training, sex, and $\dot{V}O_{2\max}$

HIIT improved $\dot{V}O_{2\max}$ more than SIT with short (8×20 s) and long (10×30 s) recovery periods in females, a novel finding in the population in question. We are not aware of any previous studies examining these protocols in females with a baseline $\dot{V}O_{2\max} \geq 50\,\text{mL}\,\text{kg}^{-1}\,\text{min}^{-1}$. In moderately trained women ($\dot{V}O_{2\max}$ of 35–45 $\text{mL}\,\text{kg}^{-1}\,\text{min}^{-1}$), HIIT 4×4 min and SIT 4×30 s have improved $\dot{V}O_{2\max}$,[10] while SIT 8×20 s have been reported unaltered following 12 sessions in three weeks.[25]

Our findings are highly relevant for exercise prescriptions where the aim is to improve $\dot{V}O_{2\max}$ and expand on previous observations in males.[8,20] The greater $\dot{V}O_{2\max}$ improvement may be explained by the greater stress on oxygen transporting organs during HIIT. Importantly, aerobic intensity must not be confused with overall intensity. Despite the intensity being higher during SIT compared to HIIT, undoubtedly with a higher degree of fatigue and exhaustion, the overloaded determinants for this noble effort may be completely different from those involved in oxygen transport. Indeed, comparing the three protocols in the present study, HIIT 4×4 min elicits the highest aerobic intensity (i.e., accumulated time ≥90% of $\dot{V}O_{2\max}$), while SIT 10×30 s elicits the least.[8] The latter result may be a consequence of the long recovery periods, allowing $\dot{V}O_2$ to fall to low levels, and insufficient length of the intervals to allow the sluggish $\dot{V}O_2$-kinetics to bring it back up during the "supramaximal" effort.

In the HIIT group, females exhibited a similar increase in $\dot{V}O_{2\max}$ as previously observed in males with similar training status.[8] This is in agreement with some previous studies,[17,18] but conflicts with others.[15,26] The 7% increase in $\dot{V}O_{2\max}$ following HIIT 4×4 min in the present study is somewhat smaller than what has been documented in healthy individuals with an aerobic power typical for what is observed in the population (~11%).[18] However, recognizing the aerobically well-trained status of the females in the current study a smaller increase is expected. Training-induced improvements in $\dot{V}O_{2max}$ are strongly associated with increases in cardiac output and, in turn, heart stroke volume.[27–29] Yet, compared with men, women may have an attenuated improvement of left ventricular mass and the Frank-Starling mechanism following 1 year of endurance training.[15] Furthermore, females have lower hemoglobin concentrations and smaller lungs than males,[29,30] two factors with limited potential for improvement.[3,30] Of note, we observed both lower hemoglobin concentration and reduced maximal ventilation in relation to body mass compared to the males in our previous study ($\mathrm{L\,kg^{-0.75}\,min^{-1}}$: females 4.7 ± 0.4, males 5.9 ± 0.6, $p < 0.001$).[8] Based on these sex-differences, it has previously been speculated that pulmonary and convective factors in the oxygen transport chain may attenuate the response to endurance training in females compared with males.[19] Yet, the findings for HIIT 4×4 min in our studies are not in support of such assumptions. Accordingly, the possible female disadvantage of the pulmonary/convective factors have been suggested to be counterweighted by other factors,[19] for example, a higher proportion of slow-twitch oxidative type I muscle fibers and capillary density compared to males.[31,32] These latter attributes may facilitate for an increased peripheral oxygen diffusion, another important component argued to contribute to the plasticity of $\dot{V}O_{2max}$.[33]

Interestingly, in contrast to observations in males,[8] SIT 8×20 s did not alter $\dot{V}O_{2max}$ in the present study, despite a similar time spent ≥90% of $\dot{V}O_{2max}$, indicating a sex-specific insufficient overload from this protocol. It is possible that females have a higher threshold for when a stimulus induce adaptations in $\dot{V}O_{2max}$ compared to males.[19] Aerobically well-trained women may be more susceptible than their male counterparts to experience exercise-induced arterial hypoxemia, especially during running,[34] which is detrimental to maximal aerobic performance. In addition, fast increments in work rate may be associated with a slightly reduced partial pressure of arterial oxygen compared to slow increments,[35] indicating that SIT is more likely to provoke exercise-induced arterial hypoxemia compared to HIIT. Combined, although no conclusion should be made, these components (work rate increment, sex, and running modality) may explain the lack of $\dot{V}O_{2max}$-improvement in aerobically well-trained women following SIT 8×20 s. In contrast to SIT, HIIT 4×4 min applies a high but submaximal intensity, and its milder work rate increment may facilitate for an adequate stimulus throughout the oxygen supply chain which are less likely to cause arterial desaturation.[35]

The finding that neither SIT protocol exerted any effect on $\dot{V}O_{2max}$ differs from studies on less trained subjects of female or pooled sex, where SIT with both short and long recovery periods have been documented to improve $\dot{V}O_{2max}$.[10,25] We chose to only include aerobically well-trained females in the current study because they were less likely to respond to any training stimulus. Great responses in all groups could potentially have clouded the differences between the protocols, along with other influencing factors such as running technique and motivation for intense training. Thus, even though SIT 10×30 s relies gradually more on aerobic metabolism already from the second interval,[36] and some has recommended this protocol for optimizing time ≥90% of $\dot{V}O_{2max}$,[11] our findings imply that SIT yield an insufficient stimulus for improving $\dot{V}O_{2max}$ in aerobically well-trained women, and that HIIT designed to overload the aerobic energy system should be recommended for improving $\dot{V}O_{2max}$.

4.2 | High injury rate and supramaximal interval training

Eight women acquired an injury while conducting the SIT 10×30 s protocol, of which seven were muscular strains in the lower extremities. To the contrary, no injuries occurred during HIIT 4×4 min or SIT 8×20 s. Previous studies with aerobically well-trained runners of both sexes conducting 30-s SIT have reported none or very few traumatic injuries.[37,38] Additionally, we are only aware of one previous study with (almost) comparable rates of traumatic injuries during SIT, in inactive and predominantly middle-aged subjects of both sexes.[39] It is, however, recognized that the risk of hamstring strains are higher during SIT compared to HIIT,[11] and sprinting is associated with an elevated risk of lower extremities muscular strains.[40] One possible contributing factor to the injuries observed are the utilization of motorized treadmills, which, in contrast to self-propelled treadmills or track running, prevents the subject from gradually decreasing the speed within each interval. This may cause the subject to "push harder" for a few more seconds rather than choosing the only other alternative, which is aborting the interval before the 30 s has passed. Another observation possibly explaining some of the injury rate is that only the SIT 10×30 s group did decrease body mass, which may indicate low energy availability and thus increased risk of injury.[41] Anecdotally, nausea was a relatively common symptom during and after SIT 10×30 s and this may have limited this groups' energy intake after training sessions. Our study implies that all-out treadmill running SIT 10×30 interspersed by long recovery breaks, eliciting a mean intensity of ~175% of MAS, may constitute an unacceptable risk of muscular strain injuries in aerobically well-trained women.

Surprisingly, the rate of muscular strains in SIT 10×30 s were considerably higher for females compared to males.[8] This finding conflicts with observational studies of athletes as males normally have a higher risk of hamstring strains compared to females.[40] Some of the elevated risk of hamstring strains commonly reported in men may be a consequence of a larger exposure to training and competitions compared to women.[42] However, this cannot explain why the rate of muscle strains were substantially higher in women compared to males of similar training status conducting a similar protocol. It is possible that this occurred because SIT 10×30 s was an unfamiliar and high-load exercise modality combined with the common finding that women exhibit reduced muscle strength compared to men.[43] Importantly, even though we included women of similar aerobic training status as the males in our previous study, the sexes may not have been similarly strength trained or accustomed to sprinting. Indeed, males typically exhibit ~30% larger MAOD than females,[13] yet we observed a 45% larger anaerobic capacity in males compared to females in the SIT 10×30 s groups. This may indicate a difference in these groups' history of anaerobic high-power exercise.

4.3 | Running economy and lactate threshold

HIIT 4×4 min and SIT 8×20 s exhibited small improvements in running economy, while SIT 10×30 s did not (Table 2). The latter finding conflicts with other studies of SIT with long recovery periods in aerobically well-trained subjects.[5,37] The lower velocity (7 km h^{-1} at 3° inclination) at which running economy was measured in our study is a possible explanation for the conflict with previous studies. HIIT 4×4 min reduced HR during the running economy test, indicative of a larger heart stroke volume at a submaximal intensity when seen in combination with the small change in running economy. LT, as a percentage of $\dot{V}O_{2max}$, did not change in any of the groups, as expected in already well-trained subjects.[8,12] Additionally, because of the improved $\dot{V}O_{2max}$ and running economy following HIIT, $\dot{V}O_2$ and velocity at LT increased collaterally.

4.4 | Interval training, sex, and anaerobic capacity

Both SIT protocols increased anaerobic capacity, assessed as MAOD, while HIIT 4×4 min showed a tendency for an improvement. The training-induced improvement in MAOD was only larger following SIT 10×30 s compared to HIIT 4×4 min with the linear calculation model and relative to body mass, and not in absolute terms or with the curvilinear calculation (Table 2). This lack of difference between SIT and HIIT contrast with our hypothesis, while the within-groups improvements following SIT protocols were expected. The result that SIT 8×20 s improved MAOD is in line with existing literature,[4,8] albeit no previous data exist on females. For all-out SIT with long recovery periods, for example, SIT 10×30 s, we are not aware of studies investigating of its effect on MAOD besides our previous study in males were MAOD remained unchanged by SIT 10×30 s.[8] Despite this discrepancy between the sexes following SIT 10×30 s, no sex-difference in this protocols' effect on MAOD were observed (Table 2). Potential determining factors underlying the improved anaerobic capacity and performance includes improved intramuscular ion-handling and transport which may cause enhanced fatigue-resistance and anaerobic metabolism.[44] However, these data are mainly derived from male subjects,[44] and further investigation of the underlining factors for increased MAOD in women may be warranted. Of note, a 30% higher baseline MAOD was observed between the sexes across the training groups. However, of importance, in each group, MAOD (mL kg^{-1}) were 23% (HIIT 4×4 min), 24% (SIT 8×20 s), and 45% (SIT 10×30 s) higher at baseline for men, and these differences may have clouded our results.

4.5 | Running performance

As aerobic and anaerobic energy systems run in parallel, and both contribute to running performance,[1] the improvements in the long-distance (3000-meter) and sprint (300-meter) time trials for all the three groups in the current study were expected. In accordance with the hypothesis, due to higher speeds and anaerobic intensity, the SIT protocols induced a larger improvement in sprint performance compared to HIIT. On the contrary, the lack of between-group differences in long-distance endurance performance was against our hypothesis. Despite a greater effect on physiological factors associated with long-distance endurance performance ($\dot{V}O_{2max}$ and running economy), which lead to improved MAS and velocity at LT, HIIT 4×4 min did not induce superior improvements on the 3000-meter time trial compared to the SIT-protocols. Although part of the SIT protocols' improved long-distance performance may be attributed to increased anaerobic capacity, an increased MAOD of 0.2–0.4 L should not elicit the same improvement as the 0.2 L min^{-1} increase in $\dot{V}O_{2max}$ for HIIT 4×4 min. This is because the 0.2 L of oxygen per minute results in a total of 2.8 L for the 14 min the 3000-meter lasted. This implies a far greater aerobic than anerobic energy contribution. Although not measured, a possible contributor to the improved long-distance time trial following SIT may be enhanced running economy at fast velocities (i.e., ~12–13 km h^{-1}), albeit running economy at 3° and 7 km h^{-1} did not improve. SIT 10 × 30 s commonly reduce the cost of running in aerobically well-trained men,[5,37] while we are not aware of any studies investigating responses in running economy to SIT 8 × 20 s. Additionally, since there is a discrepancy between the increase in physiological variables and long-distance endurance performance, tactical and/or technical affecting factors, for example, familiarization, may also explain the lack of difference between HIIT and SIT 3000-meter running performance.

4.6 | Limitations

This study has some limitations. First, even though the phases within a menstrual or oral contraceptive cycle does not affect $\dot{V}O_{2max}$, the use of oral contraceptive may dampen the training-induced adaptations of $\dot{V}O_{2max}$ and maximal cardiac output.[45] Since we did not control for oral contraceptive use, we cannot exclude the possibility that the groups were skewed in this regard. Second, there was no control of physical activity outside the study, only instructions to refrain from high-intensity training. Third, our data may only apply to aerobically well-trained women (i.e., $\dot{V}O_{2max}$ 10%–30% above average). Fourth, the injury rate may only apply to running on a motorized treadmill, and the volume of the SIT 10 × 30 s may have been unnecessarily high. Fifth, inclusion of familiarization to the time trials would probably have improved their reliability.

4.7 | Perspective

We demonstrate that aerobic HIIT (e.g., HIIT 4 × 4 min), which induces a high aerobic intensity, elicits greater improvements in $\dot{V}O_{2max}$ compared to SIT in aerobically well-trained women. Furthermore, aerobic HIIT improves $\dot{V}O_{2max}$ equally effective in females and males of similar training status,[8] indicating no need to account for sex when prescribing aerobic HIIT-sessions. However, sex should possibly be accounted for when prescribing different SIT-sessions. SIT with short recovery periods, allowing a high aerobic and anaerobic intensity for a very limited time, for example, SIT 8 × 20 s, did not alter $\dot{V}O_{2max}$ in aerobically well-trained females, contrasting the small improvement in comparable males.[8] Treadmill running SIT with long recovery periods and a relatively high volume (e.g., SIT 10 × 30 s), inducing a relatively low aerobic and high anaerobic intensity, caused an increased rate of muscular strains for females compared to males, which necessitates consideration when prescribing such protocols. Additionally, yet anecdotally, nausea was a common symptom during and after SIT 10 × 30 s. For improving anaerobic capacity, SIT should probably be the preferred protocol. Importantly, HIIT 4 × 4 min does not elicit exhaustion during the intervals, while SIT elicits exhaustion either during the last interval (SIT 8 × 20 s) or during every single interval (SIT 10 × 30 s).

5 | CONCLUSION

In conclusion, HIIT improves $\dot{V}O_{2max}$ more than SIT with both long and short recovery periods in aerobically well-trained females, while SIT improves sprint running performance more than HIIT. Treadmill running SIT 10 × 30 s induced an unacceptable rate of muscular strains, and it should therefore be carefully considered if applying this treadmill protocol is necessary.

ACKNOWLEDGEMENTS

We thank the subjects for their time, effort, and cooperation during this project. The authors declare no conflicts of interest. The results of this study are presented clearly, honestly, and without fabrication falsification, or inappropriate data manipulation.

FUNDING INFORMATION

The study was funded by The Research Council of Norway.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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How to cite this article: Helgerud J, Hov H, Mehus H, et al. Aerobic high-intensity intervals improve $\dot{V}O_{2max}$ more than supramaximal sprint intervals in females, similar to males. *Scand J Med Sci Sports*. 2023;33:2193-2207. doi:10.1111/sms.14470