# Varied speed during work intervals increases time above 90% of $VO_{2peak}$ in well-trained cross-country skiers.


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# Abstract

**Purpose**: Performing high-intensity interval training (HIT) sessions that optimizes physiological adaptations is important to improve performance in endurance athletes. This study compared the acute effects of two different high-intensity work interval protocols, with similar average speed and duration, on total time above 90% of peak oxygen uptake ($VO_{2peak}$), mean $VO_2$, $VO_2$ development during the sessions and perceptual responses.

**Method:** Eleven well-trained cross-country skiers performed in a randomized order 5x5 min work intervals on roller skis (double poling technique) using a varied-speed protocol (VAR) and a constant speed protocol (TRAD). Each 5 min work interval in VAR consisted of 3x40-s at 100% of maximal aerobic speed (MAS), interspersed with three 1 min blocks with a speed reduced to a workload between lactate threshold and MAS, while TRAD consisted of constant speed for 5 min throughout all work intervals.

**Results:** VAR induced longer time above 90% of $VO_{2peak}$ compared to TRAD during all work intervals (14.9±3.8 min vs. 12.9±4.0 min, respectively). Mean $VO_2$ was higher in VAR compared to TRAD measured as average of all work intervals during the HIT sessions (87.1±2.8 vs 85.0±2.7% $VO_{2peak}$, respectively). VAR induced higher maximum session $VO_2$ compared to TRAD (5614±392 $mL{\cdot}min^{-1}$ vs. 5451±319 $mL{\cdot}min^{-1}$, respectively). Higher mean $VO_2$-values in VAR were observed during the first 1 min 40 sec compared to TRAD. There were no differences between VAR and TRAD in mean or maximum heart rate, blood lactate concentrations or rate of perceived exertion. No differences were found between protocols in perceived musculature pain, breathing frequency or minute ventilation.

**Conclusion**: Well-trained cross-country skiers sustain longer time above 90% of $VO_{2peak}$ and induce higher mean $VO_{2peak}$ using VAR compared to TRAD, indicating that work intervals where speed variations are involved might be a good strategy for HIT sessions aiming to optimize time at high percentage of $VO_{2peak}$.

# Expanded introduction

*Cross-country skiing*

Cross-country (XC) skiing is one of the most demanding endurance sports, which involves racing in varying terrain and using different subtechniques that require both upper- and lower body work (Sandbakk & Holmberg, 2017). Some of the highest maximal oxygen uptake ($VO_{2max}$) values ever reported are held by elite XC skiers, and the $VO_{2max}$ values can reach 80-90 $mL·min^{-1}·kg^{-1}$ for men, and 70-80 $mL·min^{-1}·kg^{-1}$ for women (Tonnessen, Haugen, Hem, Leirstein & Seiler, 2015; Sandbakk & Holmberg, 2017). A high $VO_{2max}$ is associated with high level of performances in XC skiing. Ingjer (2007) compared the $VO_{2max}$ of several XC skiers and divided the athletes into three classes: world class, medium elite class and less successful elite. The study found that athletes at the highest performance level in competitions had a higher $VO_{2max}$ than athletes at a lower level, indicating that one of the most important factors determining performance in XC skiing is the sport specific $VO_{2max}$ (Losnegard & Hallen, 2014). The highest $VO_{2max}$ values in skiing is attained using diagonal skiing (Holmberg, Rosdahl & Svedenhag, 2007) and corresponding values using other subtechniques are found to be 5-15% lower. The peak oxygen uptake ($VO_{2peak}$) during double poling are found to reach 91% of $VO_{2max}$, corresponding to a double poling specific $VO_{2peak}$ of 75-80 $mL·min^{-1}·kg^{-1}$ in male XC skiers (Sandbakk & Holmberg, 2017; Skattebo, Losnegard & Stadheim, 2019). For elite skiers with an already high $VO_{2max}$, a further development in $VO_{2max}$ can be challenging. However, it might be possible to reduce the difference between $VO_{2max}$ often found using diagonal skiing and $VO_{2peak}$ using other subtechniques, with greater attention on improving $VO_{2peak}$ (in e.g. double poling seeing this technique is used more and more in various terrain during competitions) (Losnegard, Myklebust, Spencer & Hallen, 2013; Losnegard, 2019).

The varying terrain during XC skiing causes a wide range of speeds and slopes where skiers continuously alternate and adapt between different subtechniques during a race. The development of and ability to use high aerobic power while performing various skiing techniques in varying terrain are key determinants of performance in cross-country skiing (Sandbakk & Holmberg, 2014). Sandbakk et al., (2016) performed a study on elite female XC skiers, where performance on a 10 km time trial were found to positively correlated with $VO_{2peak}$ (using the classical subtechniques diagonal and double poling), and $VO_{2peak}$ using double poling technique was positively correlated with performance on all types of terrain during the 10km time trial, highlighting the importance of a high $VO_{2peak}$ in different techniques in XC skiing, and the importance of double poling capacity in all types of terrain. Further, the oxygen cost of double poling at different inclines and speeds tested in the laboratory, correlated to performance on flat terrain during the outdoor 10 km time trial. The ability to transform metabolic energy efficiently into speed, and the gross efficiency, which is the ratio of external work rate to energy expenditure, have been found to be key factor of the performance level in XC skiers (Millet, Perrey, Candau & Rouillon, 2002; Sandbakk, Holmberg, Leirdal & Ettema, 2010; Sandbakk, Hegge & Ettema, 2013b). Sandbakk et al., (2013b) found that better ranked skiers skied more efficient than lower ranked skiers and the study found significant correlations between gross efficiency and performance level, concluding performance level differences can be explained by production and utilization of aerobic energy in the specific subtechniques. The changing workloads during XC skiing may benefit skiers who can alter their $O_2$ kinetics rapidly, particularly with respect to the fractional utilization of $VO_{2peak}$, which reflects the aerobic energy used (performance $VO_2$) (Sandbakk & Holmberg, 2017).

*High-intensity interval training*

High-intensity interval training (HIT) has been used to improve endurance performance for a long time (Buchheit & Laursen, 2013). HIT involves repeated short and/or long bouts of high-intensity exercise interspersed with recovery periods. While HIT is not the only approach to improve physiological performance, HIT is considered one of the most effective forms of exercise training to enhance physiological performance in athletes (Billat, 2001; Laursen & Jenkins, 2002; Midgley & McNaughton, 2006; Buchheit & Laursen, 2013). To maximally stress the oxygen transport and utilization systems, and to possibly provide the most effective stimulus to further enhance $VO_{2max}$, it has been suggested to use HIT protocols that elicit $VO_{2max}$ or at least very high percentage of $VO_{2max}$. This can be justified by that only intensities near $VO_{2max}$ allow for both large motor unit recruitment and attainment of close to maximal or maximal cardiac output (Buchheit & Laursen, 2013). This jointly sends signals for oxidative muscle fiber adaptations (e. g. increased oxidative capacity of type II skeletal muscles, increased myoglobin concentrations, increased capillarization of skeletal muscles) and myocardium enlargements (that increases maximal stroke volume) (Midgley, McNaughton & Wilkinson, 2006; Buchheit & Laursen, 2013).

To achieve an optimal training stimulus it has been recommended that well-trained endurance athletes should perform HIT at intensities of 90-100% of $VO_{2max}$ and spend several minutes per HIT sessions at these high intensities (Wenger & Bell, 1986; Laursen & Jenkins, 2002; Buchheit & Laursen, 2013). Therefore, training times ≥90% of $VO_{2max}$ has been suggested as a good criterion to determine the effectiveness of the training stimulus to improve endurance performance (Midgley et al., 2006; Turnes, de Aguiar, Cruz & Caputo, 2016). Maximal aerobic speed (MAS) is theoretically the lowest speed required to obtain $VO_{2max}$ (Billat & Koralsztein, 1996). To achieve a longer time ≥90% $VO_{2max}$ previous studies have recommended a speed between 90% and 100% of MAS (Hill, Williams & Burt, 1997). The challenge is that well-trained runners and cyclists can only sustain continuous work at MAS around 6 min (Billat, Bernard, Pinoteau, Petit & Koralsztein, 1994), and with continuous work rates performed to exhaustion, time ≥90% $VO_{2max}$ can only be maintained for a few min (Billat et al., 2001; Midgley & McNaughton, 2006; Billat et al., 2013; Buchheit & Laursen, 2013). It has been observed that the HIT sessions inducing the longest time at high $VO_2$ obtains the largest training adaptations (Turnes et al., 2016). There are plenty of different interval protocols used by endurance athletes and it is an increasing interest in the sport science community to optimize HIT sessions in order to achieve a high as possible stimulus to develop $VO_{2max}$ and to develop the endurance performance. In this regard, developing HIT sessions that optimizes time ≥90% $VO_{2max}$ may contribute to further develop endurance performance (Buchheit & Laursen, 2013).

The distribution of work during an interval session has been found to influence maximal power output, $VO_2$ kinetics and ultimately training adaptations (Bishop, Bonetti & Dawson, 2002). Several studies have found that using a fast start pacing strategy during relatively short events result in higher average power output and higher average $VO_2$ (Bishop et al., 2002; Aisbett, Le Rossignol, McConell, Abbiss & Snow, 2009). Research supports fast start pacing, followed by a correctly timed transition to a lower speed without leading to premature fatigue, over even paced strategies in: short duration (<5 min) cycle time trials (Foster et al., 1993; Aisbett et al., 2009), speed skating competitions (Foster, Schrager, Snyder & Thompson, 1994), kayak competitions (Bishop et al, 2002) and computer simulated track cycling (de Koning, Bobbert & Foster, 1999). In these studies, a fast start induced better competition times and/or greater average power output. A fast start is likely to speed up the $VO_2$ kinetics more than a slower start and faster $VO_2$ kinetics could improve performance by increasing total $VO_2$ during a competition by increasing available ATP to fuel the exercising muscles

(Bishop et al., 2002). In addition, Zadow et al., (2015) concluded that utilizing an all-out start, total time ≥85% $VO_{2max}$ was greater compared to even paced start with trained cyclists, emphasizing that starting at a high pace may elicit longer time at $VO_2$-values close to $VO_{2max}$. However, if the starting intensity is too high and the intensity is kept for too long, it can lead to premature fatigue (Zadow et al., 2015). A fast start has been found to result in higher accumulation of fatigue related metabolites (Thompson, MacLaren, Lees & Atkinson, 2003), and the disturbance in muscle pH can become too large and interfere with contractile processes, possibly leading to a loss of technique (Foster et al., 1993), reduction in racing speed and unwanted loss of performance if the speed is not slowed down to a sustainable pace before fatigue sets in.

A few previous studies have aimed at optimizing a single HIT session for well-trained XC skiers. One study found that longer work intervals (5-10 min bouts, total duration 40-45 min) was better at improving endurance performance and $VO_2$ at the ventilatory threshold in junior XC skiers compared to shorter work intervals (2-4 min bouts, total duration 15-20 min) during a training period for 8 weeks (Sandbakk, Sandbakk, Ettema & Welde, 2013a). A recent study found that performing work intervals with a fast start followed by reduced speed acutely induced higher mean $VO_2$ than work intervals with constant speed, even though both HIT protocols used the same average speed (Ronnestad, Romer & Hansen, 2019/submitted).

Billat et al., (2013) tested two protocols, where both started at the lowest power output obtaining $VO_{2max}$ ($PVO_{2max}$). When reaching $VO_{2max}$, one protocol continued at $PVO_{2max}$, while power output was progressively varied to control $VO_2$ at $VO_{2max}$ in the other protocol. The constant power output protocol elicited under 3 min ≥95% $VO_{2max}$, while the variable power output protocol elicited 15 min. The study concluded that exercise can exceed 15 min ≥95% $VO_{2max}$ when adjusting the power output according to athletes' expired gas responses rather than using power as the controlling variable (Billat et al., 2013). However, HIT sessions using $VO_2$-values as the controlling variable is not practical in athletes' daily training. A recent study suggested that using varied intensity work intervals induced a longer time ≥90% of $VO_{2max}$ compared to constant intensity work intervals in well-trained cyclists (Bossi, Mesquida, Passfield, Ronnestad & Hopker, 2019/submitted). The study concluded that by repeatedly varying the power output within HIT work intervals, $VO_2$-values are increased compared to constant intensity work intervals matched for duration and mean power output, without finding any differences in blood lactate concentrations or perceived exertion measurements.

*Modern skiing*

The average speed in XC races has almost doubled during the last 50 years. Better preparation of ski tracks, improvements in equipment used by the athletes, improvements in athletes' upper body strength and -endurance, and technical/biomechanical enhancements are some of the reasons the speed has increased (Stoggl & Holmberg, 2016). Over the past decades, the classical subtechnique double poling has come to be utilized at a greater extent and is today decisive for success in XC races involving the classical technique (Stoggl & Holmberg, 2016). In traditional skiing, 50% of the racing time is spent uphill and is where the difference between athletes' performance is most pronounced and is the section the highest rate of work is observed, indicating training at uphill techniques is important (Sandbakk, Ettema, Leirdal, Jakobsen & Holmberg, 2011; Losnegard, 2019). The remaining 50% of the race time is spent in flat (35%) and downhill (15%) sections. The duration of different segments (uphill, flat or downhill) is typically 10 to 35-s, and rarely above 70-s in modern World Cup race courses (Losnegard, 2019). During classical races, the ability to use double poling throughout an entire race has become increasingly important (Sandbakk & Holmberg, 2017), especially during long distance races. In Ski Classics, the international long-distance XC skiing cup, consisting of 12 classical technique races, 11 of the races for men are performed using double poling only (verbal communication with Ski Classic athletes). The introduction of mass start in 10 out of 12 Olympic XC ski races, the majority of World Cup races and all Ski Classic races, has brought attention to pacing strategies that are different in mass start races compared to individual time trial races (Losnegard, 2019). Mass start competitions involve more tactics with regard to racing behind other skiers to reduce drag and save energy, obtaining a position in the field that is least problematic, optimizing each individual's strengths, being prepared for attacks from competitors, and the races are often decided during a final sprint (Sandbakk & Holmberg, 2014; Losnegard, 2019). Since all Ski Classic races are mass start, the tactics are getting more equivalent to road cycling tactics, with surprising attacks and athletes trying to get in a breakaway. Performing accelerations and faster speeds up to and above $VO_{2peak}$ for shorter periods during a race may be beneficial in establishing a leading position in the field and/or to respond to race tactics from competitors.

Elite XC skiers typically perform 750 to 900 training hours annually (the majority being endurance training) with an intensity distribution of approximately 80% at low intensity, 4-5% at moderate intensity, 5-8% at high intensity and 10% strength and speed training (Sandbakk & Holmberg, 2014). In a review paper by the same researchers (Sandbakk & Holmberg, 2017) they suggested that well-trained XC skiers should focus more on improving the quality of each HIT session, to optimize physical, mental and technical aspects, rather than increasing the number of HIT sessions. The quality of a HIT session may in this context be described by mean $VO_2$ or accumulated work time ≥90% $VO_{2max}$ (Midgley & McNaughton, 2006; Turnes et al., 2016). With the considerable intensity and terrain variations during XC races, and with more mass starts where the end result is often decided by an acceleration during or at the end of the race, varying the speed during work intervals could induce a more optimal training stimulus, give faster $O_2$ kinetics, induce higher mean $VO_2$ and time spent ≥90% of $VO_{2max}$, and at the same time mimic what athletes might face during competitions.

The main purpose of this study was to compare various physiological responses obtained by two high-intensity work interval protocols matched for duration and mean speed, but with different speed distribution during the work intervals. The hypothesis was that performing repeatedly varying speed during work intervals, athletes will obtain a longer time ≥90% of $VO_{2peak}$ and a higher mean $VO_2$ compared to using constant speed work intervals.

## Short Introduction

Some of the highest $VO_{2max}$ values ever reported are held by elite XC skiers (Tonnessen et al., 2015). The performance capability of successful XC skiers is highly related to $VO_{2max}$ and to the $VO_2$ at the lactate threshold, among other parameters (Larsson, Olofsson, Jakobsson, Burlin & Henriksson-Larsen, 2002; Ingjer, 2007; Sandbakk & Holmberg, 2014; Sandbakk et al., 2016). HIT has for a long time been used to improve endurance performance (Buchheit & Laursen, 2013). To achieve an optimal training stimulus and further develop an athlete's $VO_{2max}$, it has been recommended that well-trained athletes should perform HIT at intensities of 90-100 % of $VO_{2max}$ (Wenger & Bell, 1986; Laursen & Jenkins, 2002). Training times ≥90% of $VO_{2max}$ has been suggested as a good criterion to determine the effectiveness of the training stimulus to improve endurance performance (Midgley et al., 2006; Turnes et al., 2016;). In order to achieve a longer time ≥90% $VO_{2max}$ previous studies have recommended a speed between 90% and 100% of MAS (Hill et al., 1997). The problem is that well-trained runners and cyclists can only sustain continuous work at MAS around 6 min (Billat et al., 1994), and with continuous work rates performed to exhaustion, time ≥90% $VO_{2max}$ can only be maintained for a few min (Billat, 2001; Midgley & McNaughton, 2006; Billat et al., 2013; Buchheit & Laursen, 2013). It has been observed that the HIT sessions inducing the longest time at high $VO_2$ obtains the largest training adaptations (Turnes et al., 2016). There are plenty of different interval protocols used by endurance athletes, and there is an increasing interest in optimizing HIT sessions to get a high as possible stimulus to develop $VO_{2max}$ and enhance endurance performance. In this regard, developing HIT sessions that optimizes time ≥90% $VO_{2max}$ may contribute to further develop endurance performance (Buchheit & Laursen, 2013).

Several studies have found that using a fast start pacing strategy during relatively short events result in better competition times and/or greater average power output and higher average $VO_2$ (Foster et al., 1993; Foster et al., 1994; de Koning et al., 1999; Bishop et al., 2002; Aisbett et al., 2009). A fast start probably speeds up the $VO_2$ kinetics more than a slower start and faster $VO_2$ kinetics could improve performance by increasing total $VO_2$ during a competition by increasing available ATP to fuel the exercising muscles (Bishop et al., 2002). In addition, Zadow et al., (2015) concluded that utilizing an all-out start, total time ≥85% $VO_{2max}$ was greater compared to even paced start with trained cyclists, emphasizing that starting at a high pace may elicit longer times at $VO_2$-values close to $VO_{2max}$.

There are a few previous studies trying to optimize a single HIT session for well-trained XC skiers. One study found that longer intervals (5-10 min) was better at improving endurance performance in junior XC skiers than shorter intervals (2-4 min) during a training period for 8 weeks (Sandbakk et al., 2013a). Ronnestad et al., (2019) found that performing work intervals with a fast start followed by reduced speed acutely induced higher mean $VO_2$ than work intervals with constant speed, even though both HIT protocols used the same average speed.

Billat et al., (2013) tested two protocols, where both started at the lowest power output obtaining $VO_{2max}$ ($PVO_{2max}$). When reaching $VO_{2max}$, one protocol continued at $PVO_{2max}$ and elicited under 3 min ≥95% $VO_{2max}$, while the other protocol, where power output was progressively varied to control $VO_2$ at $VO_{2max}$, elicited 15 min ≥95% $VO_{2max}$. The study concluded that exercise can exceed 15 min ≥95% $VO_{2max}$ when adjusting the power output according to athletes' expired gas responses rather than using power as the controlling variable (Billat et al., 2013). However, HIT sessions using $VO_2$-values as the controlling variable is not practical in athletes' daily training. A recent study suggested that using varied intensity work intervals induced a longer time ≥90% of $VO_{2max}$ compared to constant intensity work intervals on well-trained cyclists (Bossi et al., 2019). The study concluded that by repeatedly varying the power output within HIT work intervals, $VO_2$-values are increased compared to constant intensity work intervals, without finding any differences in blood lactate concentrations or perceived exertion measurements.

There are considerable intensity variations during XC races, with constantly changing terrain and now with more mass starts than before, the result is often decided by an acceleration during or at the end of the race (Losnegard, 2019). Varying the speed during work intervals may induce a more optimal training stimulus, give faster $O_2$ kinetics, induce higher mean $VO_2$ and time spent ≥90% of $VO_{2max}$, and at the same time mimic what athletes might face during competitions.

The main purpose of this study was to compare various physiological responses obtained by two high-intensity work interval protocols matched for duration and mean speed, but with different speed distribution during the work intervals. The hypothesis was that performing repeatedly varying speed during work intervals, athletes will obtain a longer time ≥90% of $VO_{2peak}$ and a higher mean $VO_2$ compared to using constant speed work intervals.

# Methods

*Participants*

Eleven well-trained male skiers (age 26±4.3 years, height 186±5 cm, body mass 81±5 kg, double poling specific $VO_{2peak}$: 69.5±2.7 mL·min$^{-1}$·kg$^{-1}$; 5635±381 mL·min$^{-1}$) competing in XC skiing volunteered for this study. Ethical approval was granted by the local ethics committee of the Department of Sport Science, Lillehammer University College. The study was performed according to the ethical standards established by the Helsinki Declaration of 1975. All athletes were provided with information of the study and gave their written informed consent prior to taking part. Approval to collect and store individual data was obtained from Norwegian Centre for Research Data. The athletes reported the amount of training hours during the last 365 days to be 819±136 hours. Of the total training hours, 43.5±14% of these were performed using classical technique. During the last month preceding the study, mean training hours reported were 60.2±18 hours, and these hours were categorized into a three-zone endurance model (based on percentage of maximal heart rate ($HR_{max}$) by Sylta, Tonnessen & Seiler, 2014) of which 80% was performed in heart rate Zone 1 (60-82% of $HR_{max}$), 5% in Zone 2 (83-87% of $HR_{max}$) and 6% in Zone 3 (88-100% of $HR_{max}$). The final 9% included power, plyometrics and heavy strength training. The best results for each participant from preceding competition season were collected. The athletes' performance level varied, with the best two athletes having won a Ski Classic race. There were several top 10 (n=3) and top 20 (n=4) athletes in Ski Classic races and top 20 (n=2) athletes in Norwegian cup races.

*Experimental design*

The participants visited the test laboratory on three different occasions. Roller ski classic, double poling technique, was the exercise mode performed during the entire study. During the first visit to the test lab, participants completed preliminary tests including submaximal lactate threshold test and maximal incremental test to determine speed at lactate threshold, MAS, double poling specific $VO_{2peak}$ and $HR_{peak}$. After completing these tests, the participants performed 2x5 min HIT, in order to be familiarized with the speed and protocols of the upcoming interval sessions. On the subsequent two visits, participants performed two different 5x5 min work intervals with 3 min rest period in between. In one HIT session the participants performed work intervals with varied speed (VAR), alternating with high speed at MAS and slower speed. The other HIT session was performed with a constant speed (TRAD).

The two HIT sessions were matched for duration and average speed and the participants performed the HIT sessions in randomized order. All the laboratory testing was performed at the same time of day (±1h) to avoid circadian rhythm influences, with minimum 2 days and maximum 5 days between each test. The participants were told not to perform any intense exercise during the last 48 hours prior to each laboratory test, and they were told to prepare for each session as if the tests were important races or key training sessions. The participants were instructed to eat the same meal and drink equal amount of the same beverage before each visit, and to refrain from eating the hour preceding a session. Coffee or any product containing caffeine should not be consumed the last three hours before each test. Verbal communication before each test confirmed all athletes had followed these instructions. Participants were also told to consume the same amount, and type, of fluid during each test, and this was controlled by test leader. All tests were conducted at the test laboratory at Lillehammer University College, under similar environmental conditions (17-21°C), with a fan ensuring circulation of the air.

*Preliminary testing*

The testing, including preliminary testing, warm-up and HIT sessions during all three visits, were performed while double poling on a treadmill (Rodby RL2500E, Rodby Innovation AB, Vänge, Sweden). The treadmill belt consists of a non-slip surface band which allows the athletes to use familiar poles, with the addition of carbide tips at the end for grip to the treadmill. The same poles were used at each test and poles were optimized for every participant's racing preference (Swix Triac 2.0, Swix Sport AS, Lillehammer, Norway). To remove most variations in rolling resistance, all athletes used the same pair of classical roller skis (IDT Classic, type 2 wheels, IDT Solutions AS, Lena, Norway). The athletes used their personal ski booths. All the athletes were familiar with both the submaximal lactate threshold test and the maximal incremental test. The warm-up was standardized before the preliminary tests. A 10 min warm-up was performed starting with 4 min on the treadmill at an inclination of 2% and a speed of 12 $km \cdot h^{-1}$, then 4 min (2% inclination and 13 $km \cdot h^{-1}$) and ended with 2 min (8% inclination and 8 $km \cdot h^{-1}$). The roller skis needed to be used 10 minutes before each test to be pre-warmed to avoid variations in rolling resistance (Sandbakk et al., 2010).

The submaximal lactate threshold test was performed with a constant inclination of 8% and the first 5 min bout started at a speed of 10 $km \cdot h^{-1}$. The subsequent 5 min bouts increased by 1 $km \cdot h^{-1}$ until a blood lactate concentration ($[La^-]$) of above 4.0 $mmol \cdot L^{-1}$ was measured, then the test ended. An average of 4.5±0.8 bouts were performed. Between each bout, a 1 min brake allowed capillary blood samples to be taken from a fingertip and analyzed for whole blood [$La^-$] (Biosen C-line, EKF Diagnostics, Barleben, Germany). The average $VO_2$ from the last four measurements (2 min) of each 5 min bout, together with [$La^-$] at these bouts were later used for calculation of MAS based on the relationship between $VO_2$ and workload. $VO_2$ was measured continuously during the bouts with a sampling time of 30-s, using a computerized metabolic system with mixing chamber (Oxycon Pro, Erich Jaeger, Hoechberg, Germany). Before every test, the gas analyzer was calibrated with known concentrations of certified calibration gases. The flow turbine (Triple V, Erich Jaeger, Hoechberg, Germany) was calibrated with a 3L calibration syringe (5530 series, Hans Rudolph, Kansas City, Missouri, USA). The exact same metabolic system, with an identical calibration routine, was used during later HIT sessions.

After the lactate threshold test, 15 min of rest was given (including 10 min of active recovery on the treadmill, with an inclination of 2% and a speed of 12 $km \cdot h^{-1}$) before the maximal incremental test was performed to determine $VO_{2peak}$ and $HR_{peak.}$ Starting at a constant inclination of 8%, and speed of 11 $km \cdot h^{-1}$, the speed increased by 1 $km \cdot h^{-1}$ every minute until exhaustion (average time 7.55±0.38 min). $VO_2$ was continuously measured, and the average of the two highest 30-s measurements were used to calculate $VO_{2peak}$. A blood sample was taken from a fingertip immediately following completion of the test to establish [$La^-$]. The participants reported their peak rate of perceived exertion (RPE) on the Borg 6-20 scale (6=no exertion, 20=maximal exertion) (Borg, 1982). HR was recorded using Polar RCX5 (Polar, Kempele, Finland), and the highest HR 1-s value recorded during the incremental exercise test was defined as peak HR ($HR_{peak}$). Completing the incremental test, the participants had 15 min of rest before they performed one 5 min work interval with VAR and one 5 min work interval with TRAD in a randomized order, with the purpose to be familiarized with the protocols and speeds used during later experimental HIT sessions.

The speed at 4 $mmol \cdot L^{-1}$ [$La^-$] defined the lactate threshold in this study. This speed was calculated from the relationship between blood lactate and speed between the closest workload below and above 4 $mmol \cdot L^{-1}$ using linear regression. MAS was calculated with the same procedure described by Ronnestad et al., (2019). This method, using linear regression, extrapolates the relationship between submaximal power outputs/velocities and respective measures of $VO_2$ to $VO_{2peak}$. In the present study MAS was defined as the speed where the horizontal line representing $VO_{2peak}$ meets the extrapolated linear regression representing the submaximal $VO_2$/speed relationship. The calculation to find the speed eliciting $VO_{2peak}$ integrates measures of both $VO_{2peak}$ and the energetic cost of XC skiing in the present study and has previously been extensively used in endurance sports as a useful reference intensity for HIT sessions (Buchheit & Laursen, 2013).

*HIT sessions*

A 20 min standardized warm-up was performed to prepare the athletes for the quite steep inclination and high speed during the interval sessions. The warm-up started with 5 min at an inclination of 2% and a speed of 12 $km \cdot h^{-1}$, then 5 min at an inclination of 4% and a speed of 14 $km \cdot h^{-1}$, and 3 min at an inclination of 8% and a speed of 8 $km \cdot h^{-1}$. The warm-up continued with a progressively faster bout starting at an inclination of 8% and with a speed of 10 $km \cdot h^{-1}$. The speed increased by 1 $km \cdot h^{-1}$ every 20-s up to MAS which was held for 30-s. The warm-up ended with a 5 min active recovery period at an inclination of 5% and 15 $km \cdot h^{-1}$. The warm-up protocol was identical before both HIT sessions. Each HIT session consisted of 5x5 min work intervals, at an inclination of 8%. The average speed of both HIT protocols was equal, however the organization of the speed within the work intervals differed between the two protocols. The recovery between each work interval was 3 min in order to measure [$La^-$] and to give the athlete 90-s active recovery (self-selected speed) and time to hydrate. The speed for the next work interval was increased to starting velocity during the final 5-s of each recovery period.

TRAD consisted of a constant speed for 5 min throughout all work intervals. The speed used during TRAD was the average speed found when calculating the speeds for the VAR protocol. VAR consisted of 3x40-s at 100% of MAS, interspersed with three 1 min blocks with a speed reduced to a workload between lactate threshold (LT) and MAS (LT + 20% of the difference between LT and MAS). Each VAR started at MAS for 40-s and continued for 60-s at the reduced speed. This procedure was repeated three times during each 5 min work interval. Traditionally XC-skiers do not often perform HIT sessions until complete exhaustion, and the protocols in the present study were designed so every athlete were able to complete all the work intervals. Pilot testing revealed that a marginally higher % of MAS as average speed, or one more work interval during each HIT sessions, could be too exhaustive. The calculation of the slower speeds used during the 1 min blocks in VAR, were established after pilot testing. The reason for selecting an inclination of 8%, was due to pilot testing revealed that an inclination of 6% could result in athletes reaching a lower $VO_{2peak}$, and the speed at the end of the incremental test could be so high, that ski specific technical errors were more likely to stop the athletes than exhaustion. By increasing the inclination, increased forces are needed to move against gravity and larger muscle motor units will be recruited, possibly leading to a higher $VO_{2peak}$. It is technically demanding to produce power with short poling times (Lindinger, Stoggl, Muller & Holmberg, 2009), and with increased inclination a lower speed is needed which allow longer poling times, and ski technical errors are less likely.

The order of VAR and TRAD was randomized. HR and $VO_2$ were recorded at 20-s intervals during the work intervals. Time ≥90% $VO_{2peak}$ was determined as the sum of $VO_2$ values that were higher or equal to 90% of the $VO_{2peak}$ obtained during the preliminary incremental exercise test. To calculate time ≥90% $HR_{peak}$, the same procedure was followed. The highest 20-s $VO_2$ measurement across all work intervals was used to determine maximum session $VO_2$. The highest recording of HR across all work intervals was used to determine maximum session HR as percentage of $HR_{peak}$ obtained during the preliminary incremental exercise test. Mean $VO_2$ during the HIT sessions was calculated as the mean values across all work intervals. The development of $VO_2$ during the work intervals was evaluated as the mean values of all work intervals. It was calculated as the mean percentage of $VO_{2peak}$ during the time-blocks where the VAR protocol did not change speed. The first time-block consisted of 40-s at MAS, followed by the second time-block which consisted of 60-s at a slower speed. These blocks were repeated three times. A capillary blood sample was collected immediately at the end of each interval bout from a fingertip to assess [$La^-$], together with RPE (using Borg's 6-20 scale). One minute after completion of the HIT sessions, athletes were asked to rate their double poling specific musculature-pain on a scale from 0-10 (0=no pain and 10=maximal pain), as used in Cook, O'Connor, Eubanks, Smith & Lee (1997). 20 min after completion of both HIT sessions, session rating of perceived exertion was collected (sRPE) to measure the subjectively effort (training load) of both interval sessions (10 points Borg RPE scale, 0=rest, 10=maximal) (Foster et al., 2001).

*Statistics*

All values are presented as mean±SD in tables and text. Student's two-tailed paired t-tests were used to evaluate potential differences between VAR and TRAD in physiological and perceptual responses. Two-way repeated measures ANOVA with Bonferroni post hoc test were performed to evaluate potential differences between VAR and TRAD in mean percentage of $VO_{2peak}$ during all time-blocks where the VAR protocol did not change speed. The different blocks consist of the time between (min:sec): 0:00-0:40, 0:41-1:40, 1:41-2:20, 2:21-3:20, 3:21-4:00 and 4:01-5:00. Student's t-tests were performed in Excel 2010 (Microsoft Corporation, Redmond, WA, USA). ANOVA analyses were performed in Statistica (Tibco Software Inc., CA, USA). The statistical significance level was set at $p<0.05$. Effect size (ES) of VAR was calculate when differences between VAR and TRAD where significant with the formula: ([VAR mean - TRAD mean]/SD). To interpret the magnitude of the differences, the scale used was: 0.0-0,24 trivial, 0.25-0.49 small, 0.5-1.0 moderate, >1.0 large (Rhea, 2004).

# Results

The submaximal lactate threshold test on day one showed a mean speed of 13.2±0.9 $km \cdot h^{-1}$ at 4 $mmol \cdot L^{-1}$ [$La^-$]. The mean calculated MAS was 16±0.6 $km \cdot h^{-1}$, giving a mean speed in both HIT sessions of 14.6±0.6 $km \cdot h^{-1}$. This mean speed represented an average 91.5±2.7% of MAS. The lower speed during VAR was performed at 13.7±0.8 $km \cdot h^{-1}$ and represented an average 85.8±0.8% of MAS. Physiological responses during VAR and TRAD are presented in Table 1.

Time ≥90% of $VO_{2peak}$ was significantly higher during VAR compared with TRAD (p=0.006, Figure 1), with a moderate ES. Mean $VO_2$ was higher during VAR compared to TRAD (p=0.002, Figure 2), with a moderate ES. VAR also induced a higher maximum session $VO_2$ than TRAD (p=0.02, Figure 3), with a small ES. The development of mean $VO_2$ during both HIT sessions, expressed as percentage of $VO_{2peak}$ during all five work intervals, was higher inn VAR compared to TRAD during the first 40-s (54.0±3.3% vs. 51.3±2.6%, respectively, p=0.036; ES=0.91) and during the second time-block (0:41-1:40) (86.9±2.8% vs. 84.3±2.5%, respectively, p=0.032, ES=0.98, Figure 4). There were no significant differences between VAR and TRAD during the remaining time-blocks (1:41-2:20: 91.5±2.9% vs. 89.8±2.7%, respectively; 2:21-3:20: 93.4±3.6% vs. 91.6±3.3%, respectively; 3:21-4:00: 94.5±3.1% vs. 92.6±3.3%, respectively; 4:01-5:00: 94.9±3.9% vs. 93.4±4.1%, respectively). No differences were found between VAR and TRAD in mean ventilation or mean breathing frequency (Table 1).

Mean values during all work intervals showed no differences between VAR and TRAD in time ≥90% of $HR_{peak}$, maximum or mean HR, maximum or mean [$La^-$] measurements, nor maximum or mean RPE. No significant differences were found between reported sRPE or in reported double poling specific musculature-pain (Table 1).

**Table 1** Data from the 5x5 min HIT sessions. One HIT session consisted of varied-intensity work intervals (VAR) with 3x40-s at 100% of maximal aerobic speed, interspersed with three 1 min blocks with a reduces speed during each 5 min work interval. The other HIT session consisted of more traditional, constant-intensity work intervals (TRAD).

| | VAR | TRAD | Effect size |
|---|---|---|---|
| Time ≥90% of $VO_{2peak}$ (min) | 14.94 ± 3.83 # | 12.86 ± 4.02 | 0.52 |
| Mean $VO_2$ (% $VO_{2peak}$) | 87.1 ± 2.8 # | 85.0 ± 2.7 | 0.75 |
| Maximum session $VO_2$ ($L \cdot min^{-1}$) | 5614 ± 392 # | 5451 ± 319 | 0.46 |
| Mean breathing frequency ($cycles \cdot min^{-1}$) | 60 ± 2 | 57 ± 2 | |
| Mean ventilation ($L \cdot min^{-1}$) | 154 ± 12 | 153 ± 12 | |
| Maximum session HR (% $HR_{peak}$) | 97.4 ± 2.4 | 97.6 ± 2.7 | |
| Mean HR (% $HR_{peak}$) | 91.9 ± 1.7 | 91.4 ± 2.0 | |
| Time ≥90% of $HR_{peak}$ (min) | 19.36 ± 3.35 | 18.01 ± 3.70 | |
| Maximum session [$La^-$] ($mmol \cdot L^{-1}$) | 7.98 ± 1.64 | 8.39 ± 2.13 | |
| Mean [$La^-$] ($mmol \cdot L^{-1}$) | 7.06 ± 1.50 | 7.51 ± 1.90 | |
| Maximum session RPE (6-10) | 17.0 ± 1.3 | 17.4 ± 1.6 | |
| Mean RPE (6-20) | 16.3 ± 1.2 | 16.4 ± 1.4 | |
| Session RPE (1-10) | 6.7 ± 1 | 6.5 ± 1.3 | |
| Musculature-pain (1-10) | 4.6 ± 1.6 | 5.0 ± 1.6 | |

$VO_{2peak}$: peak oxygen uptake during the incremental $VO_{2peak}$ test; $HR_{peak}$: peak heart rate during the incremental $VO_{2peak}$ test; Maximum session $VO_2$: Maximum $VO_2$ during the work intervals, averaged over 20-s; Maximum session HR: maximum heart rate during the work intervals in % of $HR_{peak}$; [$La^{-1}$]: blood lactate concentration after the work intervals; RPE: rate of perceived extortion after the work intervals. Effect size (<0.24 trivial, 0.25-0.49 small, 0.5-1.0 moderate, >1.0 large). Values are mean ± SD. # Significant different from TRAD (p<0.05).

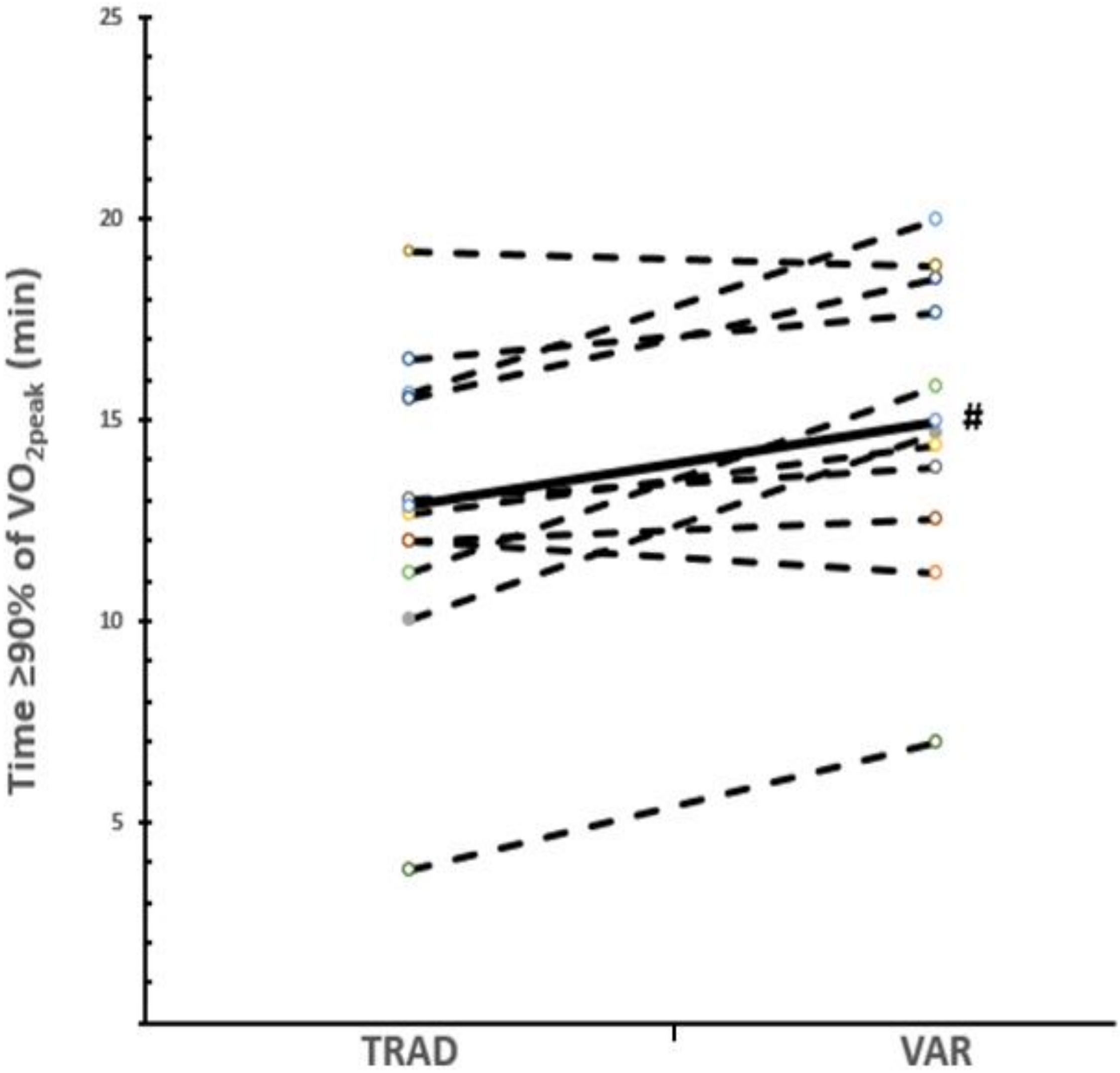


**Figure 1** Time spent above 90% of peak oxygen uptake (time ≥90% of $VO_{2peak}$) during 5x5 min HIT sessions. One HIT session consisted of varied-intensity work intervals (VAR) with 3x40-s at 100% of maximal aerobic speed, interspersed with three 1 min blocks with a reduced speed during each 5 min bout. The other HIT session consisted of more traditional, constant-intensity work intervals (TRAD). # Significant difference between HIT sessions ($p<0.01$).

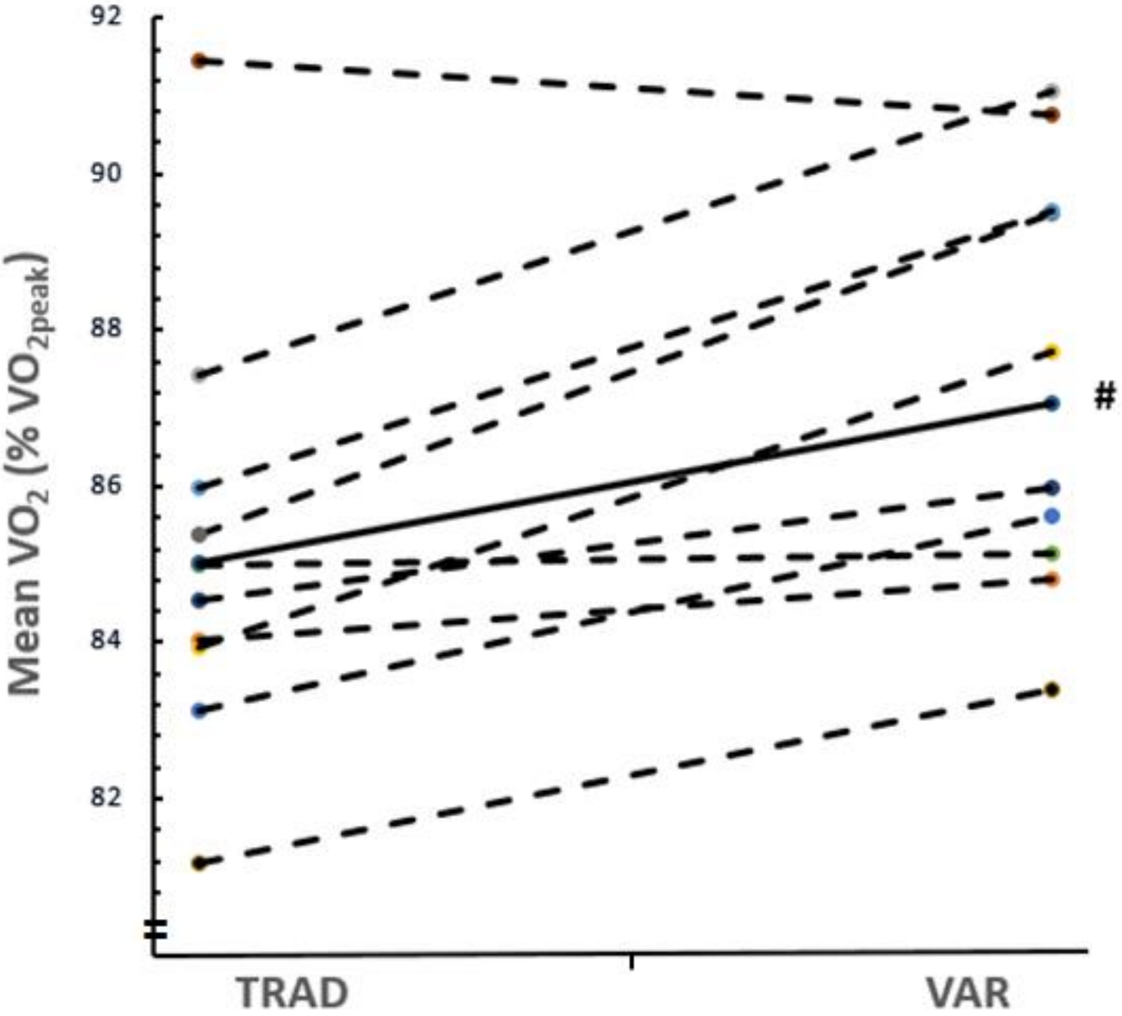


**Figure 2** Mean oxygen uptake ($VO_2$) as a percentage of peak oxygen uptake (% of $VO_{2peak}$) averaged for each individual (dotted lines) and mean values (solid line) during 5x5 min HIT sessions. One HIT session consisted of varied-intensity work intervals (VAR) with 3x40-s at 100% of maximal aerobic speed, interspersed with three 1 min blocks with a reduced speed during each 5 min bout. The other HIT session consisted of more traditional, constant-intensity work intervals (TRAD). Individual values are mean across all 5 work intervals. # Significant difference between HIT sessions ($p<0.01$).

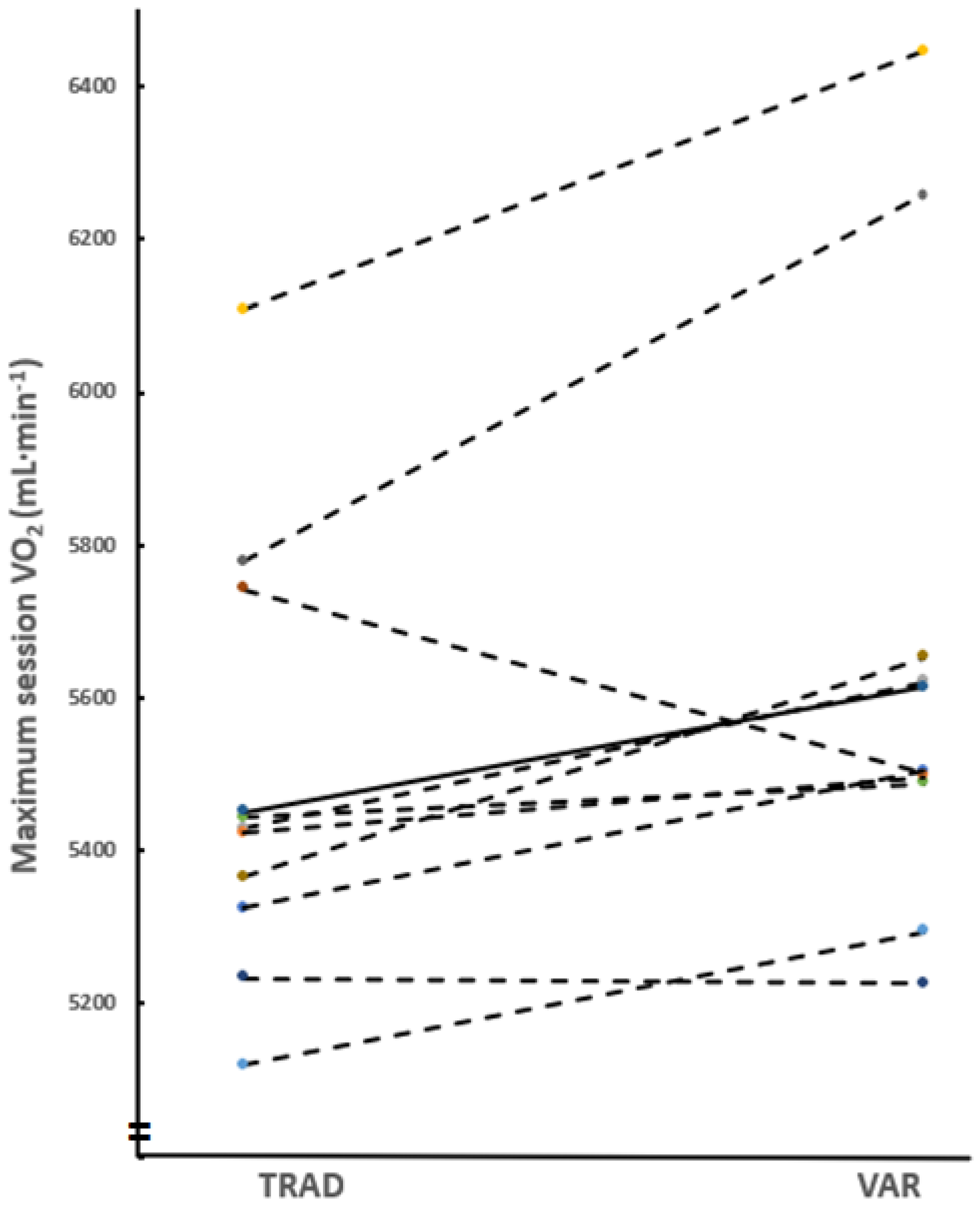


**Figure 3** Maximum session oxygen uptake ($VO_2$) for each individual (dotted lines) and mean values (solid line) during 5x5 min HIT sessions. One HIT session consisted of varied-intensity work intervals (VAR) with 3x40-s at 100% of maximal aerobic speed, interspersed with three 1 min blocks with a reduced speed during each 5 min bout. The other HIT session consisted of more traditional, constant-intensity work intervals (TRAD). # Significant difference between HIT sessions ($p<0.02$).

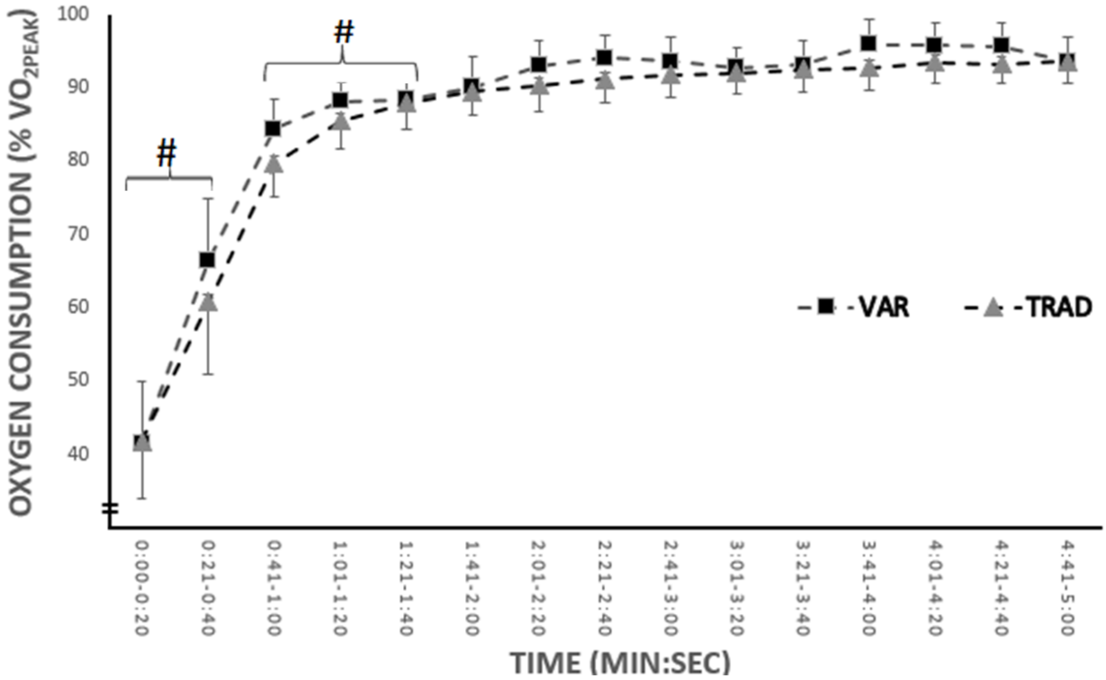


**Figure 4** The development of mean oxygen consumption as percentage of peak oxygen consumption (% of $VO_{2peak}$) in all 5x5 min work intervals during the HIT sessions. One HIT session consisted of varied-intensity work intervals (VAR) with 3x40-s at 100% of maximal aerobic speed, interspersed with three 1 min blocks with a reduced speed during each 5 min work interval. The other HIT session consisted of more traditional, constant-intensity work intervals (TRAD). # Significant difference between HIT sessions ($p<0.05$).

## Discussion

The main finding in the present study, and consistent with the hypothesis, was that well-trained XC skiers achieved a longer time ≥90% of $VO_{2peak}$ and higher mean $VO_2$ values when performing VAR compared to TRAD, even though the average speed during all work intervals was identical in both HIT protocols. Effect size calculations showed a moderate practical effect of VAR on time ≥90% of $VO_{2peak}$ and mean $VO_2$ compared to TRAD. In addition, VAR induced higher maximum session $VO_2$ compared to TRAD, and VAR induced a higher mean $VO_2$ during the first two time-blocks of the work intervals.

In VAR the speed varied between 100% of MAS and~86% of MAS, and this increased time ≥90% of $VO_{2peak}$ from 12.86 min in TRAD to 14.94 min in VAR. There are few previous studies performing similar HIT protocols with equal mean speed, length of work and recovery intervals or total HIT duration, focusing on time ≥90% of $VO_{2peak}$, which is not often the case in most studies assessing time close to or at $VO_{2peak}$ (Billat, 2001; Midgley & Mc Naughton, 2006; Buchheit & Laursen, 2013; Turnes et al., 2016). However, the fast start and reduced workload protocol used in Ronnestad et al., (2019) obtained 12.0 min ≥90% of $VO_{2peak}$, while the constant velocity protocol obtained 10.8 min. The study performed 5x5 min work intervals on well-trained XC skiers using the skating technique, with a mean velocity at around 92% of MAS. The mean velocity in the present study was at an average of 91.5% of MAS. Comparing the present study with Ronnestad et al., (2019), it is of special interest that it might seem beneficial to perform HIT sessions at a high % of MAS as possible, or at least 90% of MAS, to elicit a longer time ≥90% of $VO_{2peak}$. This is in line with previous studies recommending high speeds to sustain a long time ≥90% of $VO_{2peak}$ and to maximally stress the oxygen transport and utilization systems to provide the most effective stimulus to enhance $VO_{2max}$ (Hill et al., 1997; Billat, 2001; Laursen & Jenkins, 2002; Midgley et al., 2006, Buchheit & Laursen, 2013). Turnes et al., (2016) performed a study on recreational cyclists and observed that the largest improvements in $VO_{2max}$ and power output at lactate threshold was achieved by the training group which performed around 100-s longer time ≥90% of $VO_{2peak}$ per training session. In the present study, the VAR protocol achieved around 120-s longer time ≥90% of $VO_{2peak}$ compared to TRAD, and it can be suggested that this might be a relevant advantage in training stimulus for well-trained athletes as well. Since the smallest worthwhile enhancement in performance times for the top 10 best international skiers is 0.3% to 0.4%, athletes should focus on improvements of as small as 0.3 % (Spencer, Losnegard, Hallen & Hopkins, 2014).

Both the present study and Ronnestad et al. (2019) used a fast start (100% of MAS) during the first 40-s and 90-s, respectively, before reducing the speed. The fast start in both studies resulted in larger mean $VO_2$ during the first 1 min 40 sec and first 2 min, respectively, compared to TRAD measured as mean values across all work intervals. The fast start protocols also induced higher total mean $VO_2$-values during all work intervals compared to TRAD. This is in line with previous observations where starting short duration events (<5 min) performing a fast start pacing strategy results in a higher average power output and increases the overall $VO_2$ compared to an even intensity distribution (Bishop et al., 2002; Aisbett et al., 2009). Previous studies have also observed that utilizing a fast start followed by reduced power, total time ≥85% $VO_{2max}$ have been greater compared to even paced start in untrained and moderate trained cyclists (Billat et al., 2013; Zadow et al., 2015; Lisboa et al., 2015). The higher $VO_2$-values using a fast start could be related to a more expeditiously rise in $VO_2$ compared to a slower start, and will be discussed later. However, performing fast start during work intervals followed by reduced speed, may lead to higher mean $VO_2$ and subsequently a more optimal stimulus for cardiovascular and peripheral adaptations compared to even paced work intervals (Bishop et al., 2002; Aisbett et al., 2009; Zadow et al., 2015). It also seems that the $VO_2$ responses are independent of exercise modality, since similar responses are shown in the cardiovascular system using fast start and reducing the intensity thereafter during HIT sessions (Bishop et al., 2002; Aisbett et al., 2009; Zadow et al., 2015; Ronnestad et al., 2019).

In addition to using a fast start, VAR in the present study consisted of varied speed (3x40-s at 100% of MAS, interspersed with three 1 min blocks with a reduced speed) during the work intervals. Previous studies have also used varied intensities during work intervals. Bossi et al., (2019) performed 6x5 min HIT sessions on cyclists, which consisted of varied power output work intervals (3x30-s at 100% MAP, interspersed with two 1-min blocks and a final 1.5 min at 77% of MAP) and constant power output work intervals (performed at an intensity at 84% of MAP). The varying power output obtained 6.8 min ≥90% of $VO_{2peak}$, and the constant power output obtained 4.8 min ≥ 90% of $VO_{2peak}$. Compared to the present study, the average intensity was lower, indicating that performing work intervals above 90% of MAS/MAP might be preferred in order to increase time ≥90% of $VO_{2peak}$. However, Bossi et al., (2019) found that varying the power output during work intervals increased time ≥90% of $VO_{2peak}$ compared to constant power output, which is in line with the findings in the present study. It seems that varying the speed or power output during the work intervals, with three blocks of 30-40s at 100% of MAS/MAP interspersed with a reduced speed during 5 min work interval, could be recommended to induce a longer time ≥90% of $VO_{2peak}$. Billat et al., (2013) demonstrated that exercise can be sustained at high $VO_2$ for a long time when the power output is continuously varied and controlled according to $VO_2$-values during a test exercised to exhaustion. The variable power output was manipulated to keep $VO_2$ constant at $VO_{2max}$ using a power output between the power output associated with lactate threshold and power output associated with $VO_{2max}$. The study observed an interesting finding for practical application saying that once participants reach their $VO_{2max}$ the workload can be decreased down to the power output associated with the lactate threshold, and the participants will still be working some time at $VO_{2max}$ (which might be due to slow $VO_2$ kinetics, which will be discussed later). When $VO_2$-values reached below 95% of $VO_{2max}$ during the test, the power output increased and subsequently varied to maintain at the $VO_{2max}$ plateau during the longest time possible. This is in essence what the present study accomplished, starting at 100% of MAS for 40-s to "kick-start" the $VO_2$, and subsequently adding 40-s blocks at 100% of MAS to "boost" the $VO_2$-values when presumably the $VO_2$ would be lowered during the 1 min blocks of reduced speed.

The higher $VO_2$-values accomplished when using a fast start in VAR could be related to a faster rise in $VO_2$ kinetics compared to the even paced start in TRAD (Jones, Wilkerson, Vanhatalo & Burnley, 2008; Bailey, Vanhatalo, DiMenna, Wilkerson & Jones, 2011). Previous studies have reported that the $VO_2$ increases more rapidly towards peak using a fast start, therefore the total $O_2$ consumed in the first few minutes of the exercise is greater compared to an even paced start (Jones et al., 2008; Bailey et al., 2011). Utilizing a fast start has been seen to speed up the oxidative metabolism rise after the start of an exercise, and induce larger initial rate of muscle ATP hydrolysis, which could lead to an increase in the "error signal" between the instant supply and the required supply of oxidative phosphorylation (Whipp, 1987; Bailey et al., 2011). There are large differences between the instant $VO_2$ supply and the required $VO_2$ supply in the working muscles during the start of the work intervals in the present study, and the difference might be higher using VAR which could possibly speed up the $VO_2$ response faster in VAR compared to TRAD. After 40-s using VAR the speed reduced for 60-s, however $VO_2$-values do not appear to reduce below values attained using TRAD throughout all work intervals. Higher $VO_2$ during the second time-block using VAR compared to TRAD, could be due to a larger oxygen deficit (Jones et al., 2008) resulted by the 40-s at 100% of MAS in VAR and a compensatory increase in $VO_2$ after all the 40-s high speed efforts (Bailey et al., 2011). In later time-blocks during the first work interval and during later work intervals, the slow $VO_2$ kinetics of the first recruited muscle type II fibers may have obtained a reduced contractile efficiency and this generates a higher $O_2$ demand from the recovery process by these fatigued muscle fibers (Vanhatalo, Poole, DiMenna, Bailey & Jones, 2011). This might present an explanation to the higher mean $VO_2$ in VAR compared to TRAD across all work intervals. Bossi et al., (2019) observed higher mean minute ventilation using varied-intensity work intervals compared to constant-intensity work intervals, suggesting it led to greater mechanical work for the respiratory system, and an increased $O_2$ cost of hyperpnoea. The researchers suggested that the higher fractions of $VO_{2peak}$ found using varied-intensity work intervals could partly be explained by the increased cost of hyperpnoea. The researchers predicted an increase in $VO_2$ by 52.6 mL for each L of ventilation. The oxygen cost of breathing at maximum exercise represents a large fraction of $VO_{2max}$, averaged at 10% in young healthy males (Aaron, Johnson, Seow & Dempsey, 1992). However, the $O_2$ cost of hyperpnoea reported previously have been a lot less (2.9 mL of $O_2$ per L of minute ventilation by Aaron et al., (1992) and 2.4 mL per L of minute ventilation by Dominelli et al., (2015)). In the present study there were no differences in mean minute ventilation. Hence, the theory of increased $O_2$ cost of breathing as one explanation for the longer time ≥90% of $VO_{2peak}$ and higher mean $VO_2$ seen in VAR compared to TRAD, cannot be confirmed in the present study.

To obtain longer time close to or at $VO_{2max}$ it has been suggested to use short work intervals (Billat, 2001; Buchheit & Laursen, 2013). However, training with both short work intervals (Ronnestad, Hansen, Vegge, Tonnessen & Slettalokken, 2015) and long work intervals (Seiler, Joranson, Olesen & Hetlelid, 2013) have been seen to increase $VO_{2max}$. In XC skiers, an 8-week training intervention study observed that using HIT with longer interval bouts (5-10 min) were more effective than shorter interval bouts (2-4 min) to improve the endurance performance (Sandbakk et al., 2013a). It can be suggested that combining short work intervals with longer intervals, such as adding repeated speed variations during a 5 min work interval, as performed in the VAR protocol in the present study, might combine the benefits from both shorter and longer work intervals (Bossi et al., 2019).

There were no differences in perceived exertion between the two HIT sessions in the present study. Both peak RPE and mean RPE show that despite VAR inducing a higher mean $VO_2$, a higher maximum session $VO_2$ and a higher time ≥90% of $VO_{2peak}$, the athletes did not perceive VAR more demanding than TRAD. No differences were observed regarding mean or maximum [$La^-$], nor mean or maximum HR. This is in line with previous research indicating RPE during high-intensity work intervals is typically connected with HR and [$La^-$] (Oliveira, Slama, Deslandes, Furtado & Santos, 2013). The athletes assessed the session RPE (training load) of both HIT protocols to be similar. Also, the double poling specific musculature-pain scores were similar between the HIT protocols. To break up monotonous exercise and perform HIT sessions with the inclusion of varied speed could increase the rate of perceived amusement (Thum, Parsons, Whittle & Astorino, 2017). This might explain why athletes did not report higher RPE, sRPE, or musculature-pain, even though the athletes sustained higher mean $VO_2$ and higher maximum session $VO_2$ performing VAR compared to TRAD. There are no indications of earlier development of fatigue using VAR compared to TRAD in the present study. Fatigue was not measured directly, however, it seems that both sessions were performed with similar work intensities and with similar effort. Performing VAR might therefore not need greater attention to ensure sufficient recovery between interval sessions and later training sessions compared to TRAD (Meeusen et al, 2013).

Considering the mass start evolution, where 10 out of 12 Olympic XC competitions are mass start and all Ski Classic races are mass start, it is important for skiers to sustain repeated high-intensity periods (e.g. during start of a race to fight for positions, to break away during mid race, or fight for the result in a finishing sprint), and to recover from these periods while still racing quite fast (Losnegard, 2019). It might be beneficial to spend more training time, including HIT sessions, practicing on situations that are likely to occur during competitions. Whether using VAR produces better long-term adaptations compared to TRAD needs to be further examined in longitudinal studies. However, if varied-intensity HIT sessions, such as the VAR protocol in the present study, is incorporate into athletes' training plans it could be a great training tool to further improve the training quality with respect to optimize physical and mental aspects, and athletes might be better prepared for upcoming competitions.

In conclusion, well-trained XC skiers achieve longer time ≥90% of $VO_{2peak}$, higher mean $VO_2$ and higher maximum session $VO_2$-values when performing VAR compared to TRAD during work intervals with identical average speed and duration. There were no differences observed in mean and maximum RPE, [$La^-$] or HR. Performing VAR induces higher mean $VO_2$-values during the start of the work intervals compared to TRAD.

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