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# Maximal Work Capacity and Performance Depends Warm-up Procedure and Environmental but not Inspired Air Temperatures

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## ABSTRACT

**Lindberg, A-S, Malm, C, Hammarström, D, Tonkonogi, M**. Maximal Work Capacity and Performance in Cold and Warm Environmental and Inspired Air Temperatures. **JEPonline** 2012;15(1):26-39. The purpose of this study was to compare peak ($VO_2$ peak) and maximal ($VO_2$ max) oxygen uptake, physical performance, and lactate accumulation [la-] in warm versus cold environments. The influence of inhaled air temperature and different warm up modes on these variables as well as arterial oxygen saturation ($SaO_2$%) and pulmonary function were also studied. Two studies were performed. In study A, 10 males performed maximal exercise tests on a bicycle at +20°C and -12°C. In study B, 8 elite cross-country skiers performed maximal cross-country skiing tests at +13.7ºC. Different warm up modes (continuous and intermittent) and different temperatures of the inhaled air (-8°C and +13°C) were used. In study A, we found significantly higher $VO_2$ peak, peak carbon dioxide ($VCO_2$ peak), peak ventilation ($V_E$ peak) and respiratory exchange ratio (RER) in +20°C compared to -12°C. In study B, we found significantly lower $SaO_2$% at the end compared to the beginning of the maximal performance test. Time to exhaustion ($T_{ex}$) was significantly longer using intermittent warm up irrespectively of inhaled air temperature. In conclusion, we found that $VO_2$ max was affected by different environmental temperatures but not by different temperatures of the inhaled air and that intermittent warm up increased $T_{ex}$ without affecting $VO_2$ max.

**Key Words**: Asthma, Arterial desaturation, Cold, Cross-country skiing, Oxygen uptake

## INTRODUCTION

Physical performance is affected by the surrounding temperature, with decreased muscle function (24,25) and work capacity (21,36) in cold environment. The additional effects of wind and water will further enhance the heat transfer from the body (2,17), which will consequently affect physical performance (17). Cold exposure causes superficial and limb blood vessels to constrict in order to conserve heat, which reduces heat loss by reducing the difference between skin and environmental temperature (15).

In cross-country ski racing a very high $VO_2$ max is important for success (3). Laboratory $VO_2$ max testing at room temperature is a common way to predict performance and evaluate training-effects in cross-country skiers (7,12,16,32). The effects of cold climate on submaximal oxygen uptake ($VO_{2sub}$) and $VO_2$ max during exercise is relatively well documented, but results are inconsistent: $VO_2$ max remained unchanged (23,29,31), decreased (21) or increased (27) in the cold climate while $VO_{2sub}$ remained unchanged (29;23) or increased (21,30,31). Comparisons between different studies are difficult due to variations in study designs (e.g., different environmental temperatures). In the current study, cold is defined as temperatures below 0°C. In a review, Jett et al. (11) concluded that when investigating the effects of cold exposure on metabolism during exercise, the variety of factors shown to exert influence must be systematically isolated, controlled, and examined (e.g., training status of the subjects, duration and intensity of resting pre-exercise exposure to cold conditions, duration and intensity of cold exposure during exercise, and the insulation of clothing. Doubt et al. (6) reported that $VO_2$ during exercise is generally higher in the cold compared to warm, but that the difference decreases as the workload increases. Higher $VO_{2sub}$ in cold environment is reported to be caused by thermogenesis which will cause a greater contribution of the anaerobic glycolysis at the beginning of exercise (2). Jett et al. (11) explains that at near maximal power output, it is likely that increased thermogenesis is no longer necessary due to the metabolic heat production of exercising muscles, thus leaving $VO_2$ max unaffected by the cold.

Even though the environmental temperature differs between studies, the general consensus is that Tex during $VO_2$ max testing is reduced in cold compared to warm environments (21,23,27,29). Exercise induced bronchospasm and other asthmatic symptoms in cold climate are common problems among cross-country skiers (13,20,26,33), with a prevalence as high as 42% to 80% (13, 26). The mechanism of exercise induced bronchospasm/asthma is not absolutely clear, but exercise intensity and duration of exercise are important determinants of the severity of exercise induced asthma (1). Regardless, asthmatic problems may cause increased work of breathing (22) during exercise (17) and, therefore, decrease exercise performance due to decreased oxygen saturation ($SaO_2$%) (19). The majority of healthy people maintain $SaO_2$% above 95% even at maximal effort, while elite endurance athletes can reach levels under 90% $SaO_2$% which can limit $VO_2$ max (4,5,9,28). Exercise induced arterial hypoxemia (EIAH), has been defined as a $SaO_2$ below 95% or 3% to 4% < rest (5,19). EIAH at maximal effort has been found in runners (4), bikers (9, 28), rowers (5) and in cross-country skiers using diagonal technique, but not with double pooling technique (10). All of these studies are carried out in room temperature.

Sandsund et al. (31) found that bronchodilator by β2 agonist may increase forced expiratory volume in 1 sec ($FEV_1$) but not ventilation, $VO_2$ max or time to exhaustion in non-asthmatic cross country skiers. In healthy, non-asthmatic people ventilation is not a limiting factor for $VO_2$ max (17). It has also been shown that the warm-up procedure can influence subsequent airway function during heavy exercise (18). However, we have not found that the effects of different warm-up modes on physical performance in cold climate have been investigated previously.

Physiological performance tests of cross-country skiers are usually made in a laboratory with an ambient temperature around +20°C, but their competitive performance takes place at lower temperatures, normally -5°C to -15°C. Therefore, the purpose of this study was to compare $VO_2$ peak, maximal performance, and lactate accumulation in warm versus cold environment. The influence of inhaled air-temperature and different warm up modes on arterial saturation, $VO_2$ max, pulmonary function, lactate accumulation, and performance-time were also studied.

## METHODS

### Testing Conditions

Two studies were performed with different environmental conditions and different subjects included. To specify the actual intervention, we named the intervention group $A_{-12}$, $A_{+20}$, $B_{+14con}$, $B_{+14int}$, $B_{-8con}$ and $B_{-8int}$ based on the type of intervention, as described below.

In the first study (A), each subject performed 2 tests; once in a climatic chamber with the temperature at -12°C, relative humidity 80%, and wind 1.5 m/sec ($A_{-12}$) and once in a room with an air temperature of +20°C, relative humidity 20%, and no wind ($A_{+20}$). In the second study (Study B) each subject performed 4 tests; every test was performed in a room with a temperature of +13.9 ± 0.3°C but with different warm up modes (Tables 1 and 2). Two of the tests were executed with warm inhaled air (+13.7 ± 0.4°C); one test prepared with continual ($B_{+14con}$) and one with intermittent ($B_{+14int}$) warm up. Two tests were executed with cold inhaled air (-7.6 ± 0.4°C); one test was presided with continual ($B_{-8con}$) and one with intermittent warm up ($B_{-8int}$).

Table 1. Continual warm up session for 20 min with different temperature of the inhaled air (+13.7 ± 0.4°C and -7.6 ± 0.4°C) in a warm environment (+13.9 ± 0.3°C).

| Speed (km•h$^{-1}$) | Incline (°) | Time (sec) |
|---|---|---|
| **8.5** | 3 | 240 |
| **9.0** | 4 | 240 |
| **9.5** | 5 | 240 |
| **10.0** | 6 | 240 |
| **10.5** | 7 | 240 |

### Subjects

In study A, 10 healthy males volunteered to participate in this study after receiving a verbal and written explanation of the test procedure. Subjects with any heart disease, lung disease or obvious on going infection (virus or bacterial screening was not made) were excluded. Mean (±SD) age, height, and body weight were 37 ± 5 yrs, 181 ± 7 cm, 79.2 ± 6.2 kg, respectively, and mean $VO_2$ max of 4.17 L•min$^{-1}$ (range 44 to 61 mL•kg$^{-1}$•min$^{-1}$).

In study B, 8 healthy national and international male cross-country skiers accustomed to $VO_2$ max testing volunteered to participate. Mean (±SD) age, height, and body weight were 21 ± 5 yrs, 181 ± 8 cm, 75.2 ± 9.2 kg, respectively. $VO_2$ max was 5.03 L•min$^{-1}$ with a range 60 to 81 mL•kg$^{-1}$•min$^{-1}$. Written and verbal instructions regarding the study and possible risks and discomfort were given prior the tests. The tests were conducted in accordance with the World Medical Association Declaration of Helsinki regarding human subjects. Ethical permission

Table 2. Intermittent warm up session for 20 min with different temperature of the inhaled air (+13.7 ± 0.4°C and -7.6 ± 0.4°C) in a warm environment. (+13.9 ± 0.3°C).

| | | |
|---|---|---|
| **8.5** | **3** | **240** |
| **9.0** | 4 | 240 |
| **9.5** | 5 | 240 |
| **10.0** | 6 | 240 |
| **11.0** | 10 | 30 |
| **11.0** | 3 | 75 |
| **11.0** | 10 | 30 |
| **11.0** | 3 | 75 |
| **11.0** | 10 | 30 |

was granted by the local ethical committee at Dalarna University, Falun, Sweden (2006-03-31).

**Procedures**

*Instrumentation*

In both studies, the $O_2$ and $CO_2$ gas analysers (Jaeger Oxycon Pro, Intramedic AB, Bålsta, Sweden) were calibrated in relation to known gases (Air Liquid, Alpha mix) with a two point calibration prior to each test. Volume calibration was automatically conducted with constant flow of 0.3 and 2.0 L•sec$^{-1}$. The system is regularly calibrated for airflows up to 10 L•sec$^{-1}$ by manual calibration. In study A, environmental temperature and relative humidity were checked with GMH 3330 and GMH 3160-12 (Svenska termoinstrument AB, Täby, Sweden). During the $VO_2$ tests, a two way Y-valve, mouthpiece, nose clip and tubes were connected to the subjects with a headgear (Hans Rudolph Inc, Kansas City, USA). Pulmonary function was assessed by forced vital capacity (FVC) and forced expired volume in one second (FEV1) with a Jaeger Oxycon Pro in the second study only. Heart rate was registered with Polar heart rate monitor S810 (Polar Electro Oy, Kempele, Finland). In the second study, temperature of the inspired air was measured with a thermistor (Termometerfabriken Viking AB, Eskilstuna, Sweden) located at the inspiring valve. Bodyweight of the subjects was measured with a flat-scale (Seca Corporation, Hanover, USA). During the second study, arterial saturation was measured on the fingertip using a pulse-oximeter (Datex-Ohmeda, Luiseville, USA) synchronized to the Oxycon Pro. Lactate-accumulation was analysed with Biosen 5130 and Biosen 5140-1506 (EKF-Diagnostic, Magdeburg, Germany). The bicycle tests were performed on a Monark 828E (Monark ecercise AB, Varberg, Sweden), and the cross-country skiing tests were performed on a motor driven treadmill (Refox, Falun, Sweden). In the first study, concentration of capillary haemoglobin concentration in blood (B-Hb) was analyzed with a B-Hemoglobin Fotometer (Hemocue AB, Ängelholm, Sweden).

***Experimental Design***

During both studies, restrictions regarding food and exercise prior to the tests were given. In study A, the subjects were instructed not to exercise the day before, no hard training 3 days before and not to do any unaccustomed exercise 4 days before each session. In study B, the subjects were told to standardize training and content of food on their own. Each subject signed a medical check-up and body weight was checked before each session in order to calculate correct $VO_2$ and $VCO_2$ values.

In study A, each subject performed two maximal exercise ramp tests on a bicycle ergometer in random order at the same time of the day on two separate days, 2-7 days between the tests. The subjects wore the same clothing during both sessions apart from gloves, which were used in the climatic chamber only. Prior to and 1 min after each test capillary blood was sampled from a fingertip. The 15 min warm up took place in the warmer area (20°C) at the same self-chosen intensity during both sessions. Immediately after entering the climatic chamber the subjects performed a maximal ramp test. The tests started at 100 W and each min the resistance was increased by 25 W until exhaustion. The test stopped when the subjects were unable to keep up the 60 rpm cadence. The physiological parameters measured during cycling were $VO_2$ peak, peak heart rate (HR peak), $V_E$ peak, $VCO_2$ peak and RER. Values were calculated as 30-sec means for each variable. Other variables registered were $T_{ex}$, $[la-]_b$ and B-Hb.

In study B, each subject performed four maximal cross-country skiing ramp-tests until exhaustion. Tests were performed in random order but at the same time of the day on four different days, 1-7 days between the sessions. The subjects wore the same self-chosen clothes in all sessions. After each test, fingertip capillary blood was sampled at 1, 5, and 10-min. The tests were administered with 2 different modes of warm up: continual and intermittent cross country skiing for 20 min (Tables 1 and 2) and 2 different temperatures of the inhaled air. Each test started 5 min after the warm up. The

maximal exercise ramp test started at 11 km•h$^{-1}$ and with 4° inclines which then increased 1° each min during the test. The test stopped when the subject stopped at voluntary exhausted. FEV1 and FVC were measured prior to and at 5 min after the maximal ski test. Physiological parameters measured during the ramp tests were $VO_2$ max, maximal heart rate (HR max), maximal ventilation ($V_E$ max) maximal carbon dioxide production ($VCO_2$ max), RER, SaO2%, $[la-]_b$, and performance time ($P_{sec}$).

**Statistical Analyses**

The data are presented as mean ± standard deviation. Statistical analyses were performed using JMP (SAS Institute, USA). Differences between tested conditions were investigated with repeated measurement ANOVA and paired t-test.

## RESULTS

Physical and physiological characteristics of the subjects and maximal exercise test results from study A are presented in Table 3. We found that $VO_2$ peak ($P<0.05$), $VCO_2$ peak ($P<0.01$), RER ($P<0.05$) and $V_E$ peak ($P<0.05$) were significantly higher in session $A_{+20}$ compared to $A_{-12}$ (Table 3, Figure 1) while HR peak, $[la-]_b$, B-Hb and $T_{ex}$ were not significantly different between sessions (Figure 2).

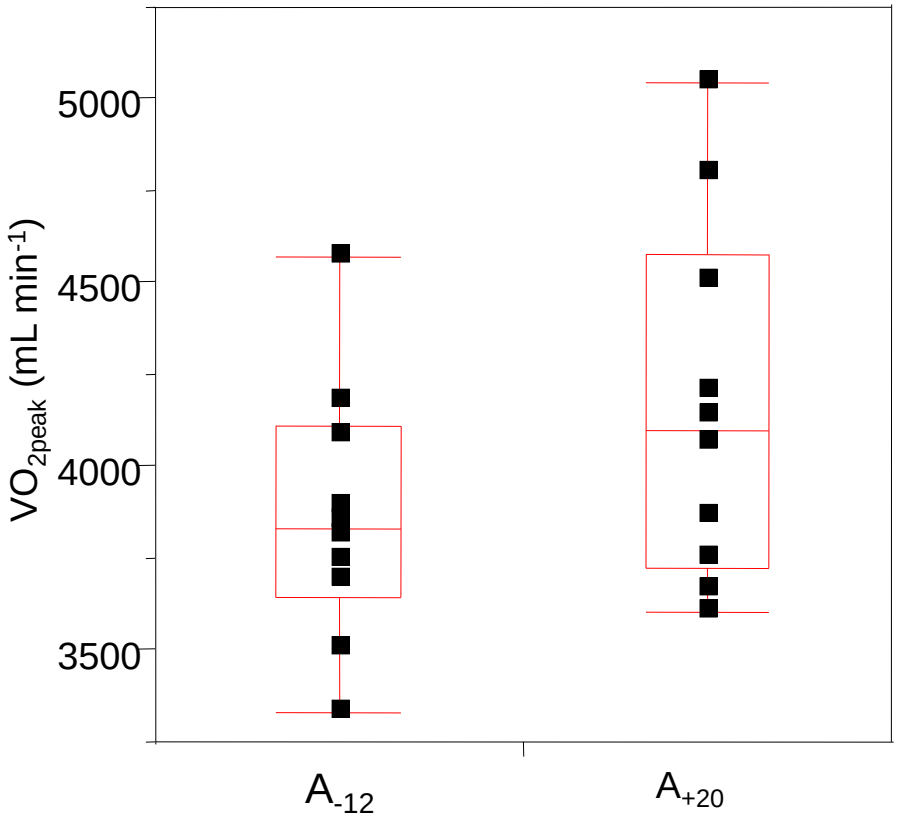


Figure 1. Peak oxygen uptake ($VO_2$ peak) was significantly higher in room ($A_{+20}$) compared to cold ($A_{-12}$) environment ($P<0.05$). Boxes show median and 75% CI. Whiskers at 95% Confidence Interval (CI).

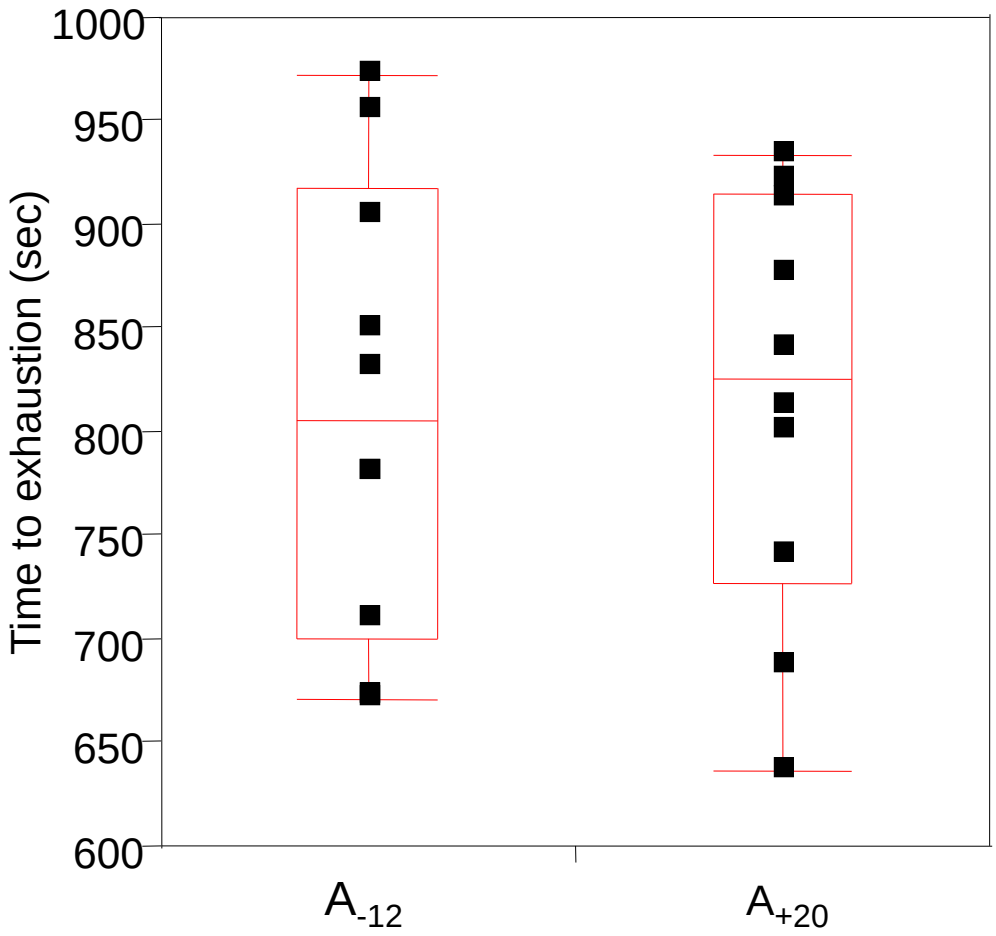


Figure 2. Time to exhaustion ($T_{ex}$) was the same in warm ($A_{+20}$) and cold ($A_{-20}$) environment. Boxes show median and 75% CI. Whiskers at 95% CI.

There was a significant correlation between results in warm and cold ($A_{+20}$ vs. $A_{-12}$) environment regarding $VO_2$ peak (mL• $kg^{-1}$•$min^{-1}$, $R^2$ = 0.43, P = 0.02), $VO_2$ peak (L•$min^{-1}$, $R_2$ = 0.35, P = 0.04) and $T_{ex}$ (sec; $R^2$ = 0.64, P = 0.03).

Table 3. Physiological maximal exercise test results from study A. Tests were made in a room-temperature of 20°C ($A_{+20}$) and -12°C ($A_{-12}$).

| Group | B-Hb g•l$^{-1}$ | $VO_2$ peak ml•min$^{-1}$ | $VO_2$ peak mL•min$^{-1}$•kg$^{-1}$ | $VCO_2$ peak mL• min$^{-1}$ | RER | $V_E$ L•min$^{-1}$ | HR peak beats•min$^{-1}$ | $[la^-]_b$ mmol•l$^{-1}$ | $P_{sec}$ Sec |
|---|---|---|---|---|---|---|---|---|---|
| ***$A_{+20}$*** | 152±9 | 4166±487* | 52.7±6.1* | 4471±449** | 1.07±0.04* | 175±25* | 180±10 | 12.1±1.5 | 623±96 |
| ***$A_{-12}$*** | 152±10 | 3869±352* | 48.9±5.5* | 4093±379** | 1.06±0.05* | 156±23* | 177±13 | 11.2±2.5 | 614±90 |

N=10. B-Hb: Hemoglobin concentration, $VO_2$ peak: Peak oxygen uptake, $VCO_2$ peak: peak carbon dioxide production, RER: respiratory exchange ratio, $V_E$: expired minute ventilation, HR peak: Peak heart rate, $[la^-]_b$ : lactate concentration in blood. $P_{sec}$: Performance time. Significance between $A_{+20}$ and $A_{-12}$ *P<0.05 **P<0.01

Table 4. Physiological maximal exercise test results from study B. Every test was made in a room temperature of +13.9°C. Two of the tests executed with +13.7°C temperature of the inhaled air prepared with continual warm up ($B_{+14con}$) or intermittent warm up ($B_{+14int}$). Two of the tests were executed with cold -7.6°C temperature of the inhaling air, prepared with a continual warm up ($B_{-8con}$) or with intermittent warm up ($B_{-8int}$).

| Group | $VO_2$ max mL•min$^{-1}$ | $VO_2$ max mL•kg$^{-1}$•min$^{-1}$ | $VCO_2$ max mL•min$^{-1}$ | RER | $V_E$ L•min$^{-1}$ | HR max beats•min$^{-1}$ | $SaO_2$ $\%_{in}$ | $SaO_2$ $\%_{max}$ | $[la^-]_b$ mmol•l$^{-1}$ | $P_{sec}$ Sec |
|---|---|---|---|---|---|---|---|---|---|---|
| $B_{+14con}$ | 4970±616 | 66.1±2.9 | 5524±910 | 1.11±0.06 | 160.8±21.8 | 193±7 | 97.0±0.7 | 93.8±3.7§ | 9.6±2.9 | 401±61.6 |
| $B_{+14int}$ | 5092±573 | 67.3±3.4 | 5767±839 | 1.13±0.04 | 164.7±16.1 | 194±4 | 97.9±0.7 | 95.5±4.2 | 9.3±2.7 | 435*†±75.2 |
| $B_{-8con}$ | 4925±564 | 65.4±2.3 | 5260±776 | 1.07±0.06 | 159.4±15.0 | 193±5 | 97.1±0.5 | 95.5±3.4 | 9.3±1.6 | 394†‡±53.8 |
| $B_{-8int}$ | 5020±518 | 66.8±2.5 | 5636±660 | 1.12±0.04 | 166.4±14.3 | 195±4 | 96.8±2.0 | 93.5±5.7 | 9.9±2.0 | 451*‡±752 |

N=8. $VO_2$ max: maximal oxygen uptake, $VCO_2$ max: maximal carbon dioxide production, RER: respiratory exchange ratio, $V_E$: expired minute ventilation, HR max: maximal heart rate, $SaO_2$%: arterial saturation of the blood before ($SaO_2\%_{in}$) and in the end of the maximal exercise test ($SaO_2\%_{max}$), $[la^-]_b$ : lactate concentration. Significance between $B_{-8int}$ and $B_{+14con}$ *P<0.05. Significance between $B_{+14int}$ and $B_{-8con}$ †P<0.05. Significance between $B_{-8int}$ and $B_{-8con}$ ‡P<0.05. §Significant between Max and Initial values (P<0.01)

Physical and physiological characteristics of the subjects and maximal exercise test results from study B are presented in Table 4. We found in warm environment and with continuous warm up (B+14con) that $SaO_2$% was lower at the end of the maximal exercise test than before (P<0.01). No significant differences in $SaO_2$% between different warm up modes and temperatures of the inhaled air were found. Therefore, we also consolidated and analyzed these results together to compare $SaO_2$% between initial and final work load. A significant difference (P<0.0001) was then found; 97.2 ± 0, 4% at initial work load compared to 94.6 ± 0.7% at the final work load (Table 4, Figure 3). Every test prepared with intermittent warm up resulted in longer Tex compared to the continual warm up (P<0.05). When inhaling cold air, Tex was 14.8% longer (P<0.05) with intermittent compared to the continual warm up (Figure 4). $VO_2$ max, $VCO_2$ max, RER, $V_E$ max, HR max, [la-]$_b$, $FEV_1$ or FVC were not affected by different warm up modes or different temperatures of the inhaled air (Tables 4 - 5).

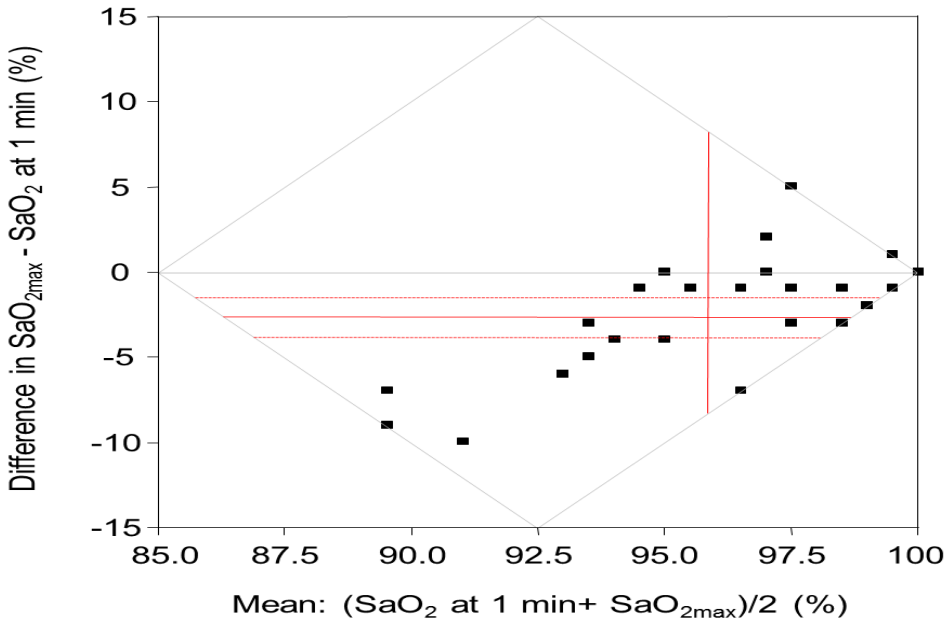


Figure 3. $SaO_2$% was significantly lower (P<0.0001) after the maximal exercise test (94.6 ± 0.4%) compared to the initial work (97.2 ± 0.7%). Solid horizontal line indicates mean difference and dashed lines 95% CI. Vertical line is mean of mean of pairs on the x-axis. The 45-degree tilted square shows the frame of the tilted scatterplot of the original columns.

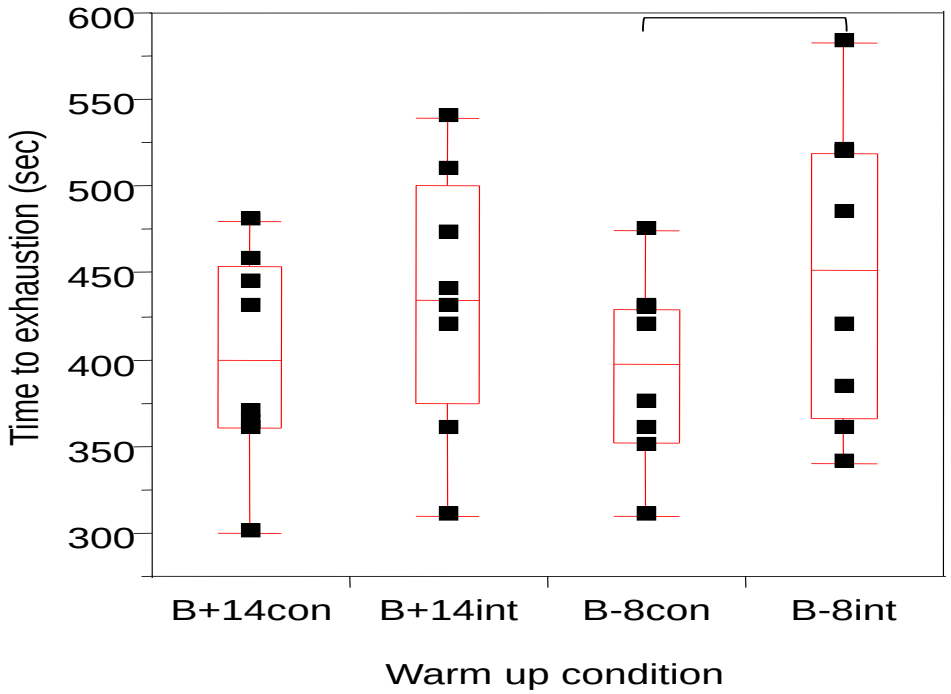


Figure 4. When inhaling cold air, time to exhaustion ($T_{ex}$) was significantly longer ($P<0.05$) with intermittent compared to the continual warm up, indicated with bracket ($B_{-8con}$ versus $B_{-8int}$). Boxes show median and 75% CI. Whiskers at 95% CI.

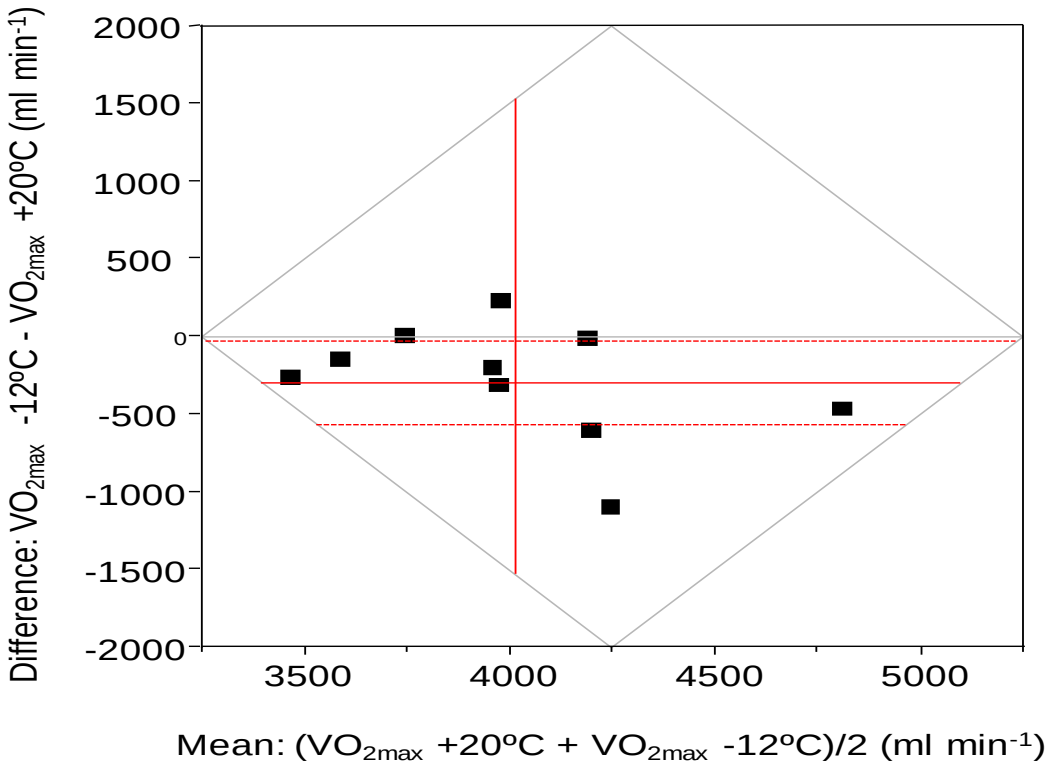


Figure 5. Difference in $VO_2$ max ($mL \cdot min^{-1}$) between Warm (20ºC) and Cold (-12ºC) environment plotted against the mean of mean. Solid horizontal line indicates mean difference and dashed lines 95% CI. Vertical line is mean of mean of pairs on the x-axis. The 45-degree tilted square shows the frame of the tilted scatterplot of the original columns.

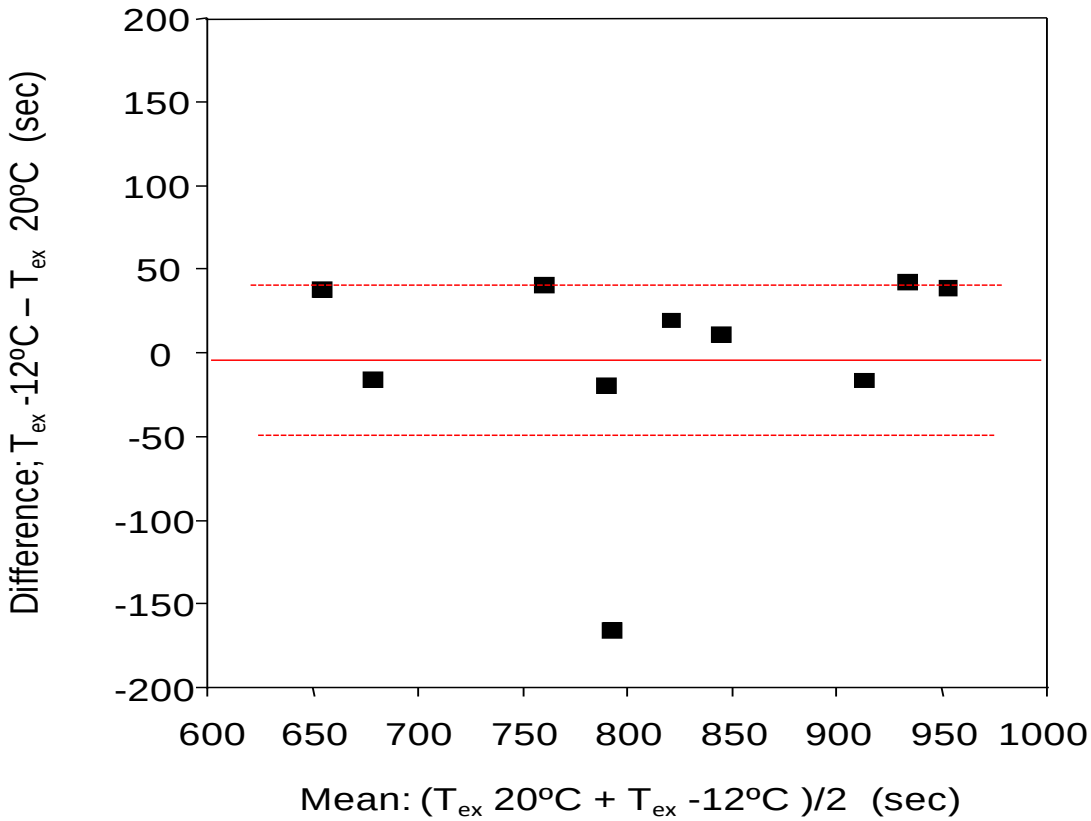


Figure 6. Difference in Time to exhaustion (Tex; sec) between Warm (20ºC) and Cold (-12ºC) environment plotted against the mean of mean.

Table 5. Forced vital capacity (FVC) and Forced expired ventilation in one second ($FEV_1$) in liter (L) before (Pre) and after (post) the maximal exercise test in study B. Tests were made in room temperature (+13.9).

| N=8 | Pre FVC (L) | Post FVC (L) | Pre $FEV_1$ (L) | Post $FEV_1$ (L) |
|---|---|---|---|---|
| $B_{+14con}$ | 6.0 ± 0.81 | 6.4 ± 0.81 | 4.8 ± 0.43 | 5.2 ± 0.50 |
| $B_{+14int}$ | 6.2 ± 0.76 | 6.2 ± 0.88 | 4.9 ± 0.4 | 5.0 ± 0.59 |
| $B_{-8con}$ | 6.2 ± 0.82 | 6.4 ± 0.88 | 4.9 ± 0.47 | 5.1 ± 0.48 |
| $B_{-8int}$ | 6.3 ± 0.72 | 6.4 ± 0.82 | 4.9 ± 0.33 | 5.1 ± 0.43 |

## DISCUSSION

The main findings in study A were that $VO_2$ peak, $VCO_2$ peak, RER and $V_E$ peak were significantly higher in the warm session ($A_{+20}$) compared to the cold session ($A_{-12}$) without changes in any of the other variables. The higher $VO_2$ peak in the warm environment compared to the cold environment is in agreement with the study by Oksa et al. (21), but disagrees with the findings regarding $VO_2$ max where it has reported to be unaffected (23,29,31) or increased (27) by cold environment. A variation in $VO_2$ max with different forms of exercise has been reported in the literature as a reflection of the quantity of muscle mass activated (11). Thus, studies using treadmill tests (11,29,31) cannot be compared with bicycle tests as was done in the present study. Treadmill running increases the possibility of reaching absolute $VO_2$ max compared to bicycling. Patton and Vogel (23) used a mechanically braked ergometer bicycle and found $VO_2$ max unaffected by cold environment. One

reason might be that they used 2 to 3 kg of arctic clothing in the cold that may have affected their results by increasing work resistance, thus increasing the chance of reaching $VO_2$ max. Also, when wearing heavy clothing, cooling of the body will most likely not occur during the short exposure of a max test of 8 to12 min and the only cold exposure will be via the inhaled air. In study A, the subject used the same clothing during both at cold and warm sessions (except gloves). Some researchers (2,6,11) have reported that $VO_{2sub}$ is generally higher in the cold environment and the reasons might be multifactor (e.g., thermogenesis, higher contribution of the anaerobic glycolysis, larger fraction of fast-twitch fiber recruitment, and respiratory heat loss). The difference in $VO_2$ between warm and cold environment decreases as workload increases. This leaves $VO_2$ max largely unaffected, while $VO_{2sub}$ and $VO_2$ peak may be decreased in the cold environment.

In general, stroke volume is lower when exercising in a warm climate because arterial blood will be distributed to the skin and, therefore, unable to deliver its oxygen to the active muscles (17). Warming up prior to the exercise tests in study A was carried out at room temperature during both $A_{+20}$ and $A_{-12}$ and the maximal exercise test lasted for 600 to 700 sec, and subjects were exposed for different environmental temperatures only for a short time because the test started immediately after entering the climatic chamber. An increase in core temperature is necessary to reach $VO_2$ max (36). Unfortunately rectal temperature was not investigated in study A, and we can consequently not draw any conclusions regarding the effects of body temperature on physical performance or $VO_2$ max. Because of the short cold exposure, core temperature is probably not affected by the climate but only by the exercise. Hence, it not likely that the higher $VO_2$ max in $A_{+20}$ compared to $A_{-12}$ was related to a higher core temperature.

In study A, $[la-]_b$ was the same in $A_{+20}$ and $A_{-12}$. Lactate was analyzed immediately and 5 min after the exercise test. One limitation is that during cold exposure peripheral vasoconstriction in the fingertip may occur, lactate samples from the fingertip may therefore not be representative of the body as whole (11). Jett et al. (11) suggests that when investigating metabolism or substrate utilization, the influences of environmental conditions have to be controlled. Also, duration and intensity of cold exposure at rest and prior to exercise, the degree of acclimation of subjects to cold conditions and the clothing status of the subjects have to be standardized. In future studies, a standardized definition of cold is also important if the purpose is to compare performance and physiological variables in relation to performance in winter sports.

In study B, physical performance time, measured as time to exhaustion ($T_{ex}$) was higher using an intermittent warm up compared to a continuous warm up when inhaling cold air (Figure 4). It is interesting, and for the cross country skiers important in a competition that performance (e.g., $T_{ex}$) was affected by different warm up models when inhaling cold air. The intermittent warm up resulted in a better $T_{ex}$ in the incremental maximal performance test compared to the continuous warm up. The reason for this finding may be that the intermittent warm up model activates the anaerobic system by breaking down creatine phosphate, increasing creatine, inorganic phosphate, and adenosine diphosphate in the working muscle cells without accumulating lactic acid due to the brief rest periods between the high intensity bouts (37). The high intensity bouts may have also contributed to a creatine phosphate recovery over-shoot (8,34,35). Maximal oxygen consumption ($VO_2$ max), $VCO_2$ max, RER, $V_E$ max, HR max, $[la-]_b$, $FEV_1$ and FVC were not affected by different warm up modes or different temperatures of the inhaled air. We have not found that the effects of different warm up modes on physical performance in cold climate have been investigated earlier.

In study B, we found significantly lower $SaO_2$% at the end compared to the beginning of the exercise performance test. That is in accordance with Holmberg et al. (2007) using diagonal skiing. In 15 of the total of 32 tests in study B, cross-country skiers EIAH was reached with a mean $SaO_2$% of 94.6 ±

0.7% including all of the tests. In 10 of the cases, the subjects reached moderate EIAH ($SaO_2$% between 88% and 93%), 3 cases reached mild EIAH ($SaO_2$% between 93% to 95%), and in 2 cases severe EIAH ($SaO_2$% < 88%) according to the definition of Dempsey and Wagner (4). Dempesy et al. (5), Rice et al. (29), and Guenette et al. (9) all found EIAH in subjects tested on running and biking. Using pulse oximetry during exercise testing has the advantage that it provides for a continuous reading of the data. The drawback is that the evaluation is indirect and might be sensitive to an exercise induced reduction in skin blood flow at the onset of exercise or cold environment. All earlier studies investigating $SaO_2$% were conducted in warm environments. The authors' explanation for the observed variations in saturation during maximal effort in endurance athletes is not clear. However, if the subjects' experienced vasoconstriction in the skin, then, this factor may influence $SaO_2$% and help to explain the different findings.

For endurance athletes, the pulmonary system is not as developed as the cardiovascular system, possibly contributing to inequalities in ventilation-perfusion ratio within the lungs, shunting of blood and/or diffusion limitations (17). In study B, only the breathed air differed in temperature and even if $VO_2$ max was equal in all four sessions we actually do not know if $VO_2$ max was affected by EIAH. In one study, $VO_2$ decreased by 2% for each 1% decrease of $SaO_2$, at least when arterial desaturation exceeds 95% (19). In the present study, a weak but significant correlation ($R = 0.11$, $p=0.037$) shows that each 1% decrease in EIAH increased $VO_2$ max by 1.5%, indicating a larger $O_2$ extraction with higher $VO_2$ max. The correlation between aerobic capacity in warm and cold environment suggests that testing winter sport athletes (e.g., cross country skiers) at room temperature will give results correlated to performance in competition, just at a slightly different level. However, looking at the large deviations from the regression line $VO_2$ max (Figure 5) and time to exhaustion (Figure 6), it becomes evident that there are significant individual differences. Thus, one subject tested at room temperature may or may not perform equally in cold climate and testing winter sport athletes at room temperature can therefore be misleading.

## CONCLUSIONS

We found that $VO_2$ max was affected by different environmental temperatures, but not by different temperatures of the inhaled air. Peak oxygen consumption ($VO_2$ peak), $VCO_2$ peak, RER and $V_E$ peak during biking were significantly higher at a room temperatures of +20ºC compared to -12ºC. Another finding was that before maximal cross-country skiing, intermittent warm up increased physical performance without affecting $VO_2$ max, irrespectively of the temperature of the inhaled air.

In cross-country ski racing, a high $VO_2$ max is important for success. Based on data from this study, testing $VO_2$ max in room temperature will result in higher $VO_2$ max than can actually be reach when competing in cold environments. Due to the large individual differences in performance and $VO_2$ max, results relevant for competition can only be measured in competition environment. An intermittent warm up model is recommended for the athletes and testing in competition settings suggested for researchers and coaches.

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