Contents

Abstract

Purpose: The purpose of this study was to investigate the effects of exposure to cold and warm environments on performance-related variables in cross country skiers, wearing standardized skiing clothing. We hypothesized that reducing ambient temperature, skin temperatures will gradually decrease despite increasing core temperature. In addition we hypothesized that the optimal ambient temperature for aerobe endurance performance with the existing cross country skiing suit would be at temperatures around 0 ºC. **Methods**: Nine highly trained male endurance athletes performed one pre-test at 20 °C (±0.1) and six main tests under controlled ambient temperatures at -14 °C (±0.2), -9 °C (±0.1), -4 °C (±0.1), 1 °C (±0.2), 10 °C (±0.1) and 20°C (±0.1). Tests consisted of running on a treadmill with an inclination of 10.5% and a wind speed at 5.5 m·sek^{-1}. The exercise protocol consisted of a 10 min warm up phase (60% of maximal oxygen consumption), a submaximal phase with four steps of 5 minutes with an intensity between 67- 91% of maximal oxygen consumption, and a maximal phase, running to exhaustion. Skin temperatures, rectal temperature, time to exhaustion, oxygen consumption, heart rate, blood lactate, loss of body mass, perceived strain and perceived thermal sensation were measured during the tests. **Results**: Mean skin temperature decreased significantly with reduced ambient temperatures, despite an increase in rectal temperature. Time to exhaustion was significantly longer at -4 °C and 1°C than at -14 °C, 10 °C and 20 °C. Running speed at lactate threshold was significantly higher at -4 °C than at -9 °C, 10 °C and 20°C. Submaximal oxygen consumption was significantly higher at 10 °C and 20 °C than the other ambient conditions, but no significant difference in VO$_{2max}$ between the ambient conditions were found. **Conclusion**: The results of the present study indicates an optimal aerobe endurance performance with the existing cross country skiing suit at -4 ºC and 1 ºC. At higher (10°C and 20°C) and lower (-14 °C and -9 °C) ambient temperatures the aerobe endurance performance was impaired.

Introduction

Cross country skiing is an outdoor winter sport, which usually is accomplished in cold weather. The lowest allowed temperature to race in is -20 ºC and the outfit that is commonly used consists of a cross country skiing suit and underwear. On the other hand, ambient temperature can also be as high as 5-10 ºC in cross country skiing competitions. In addition to the variation in temperature, the duration of the race can be as short as 3 min (sprint) or as long as 2 hours (50 km) according to Federation Internationale Ski cross country skiing world cup. Therefore, the combination of different environmental conditions and durations can expose the skiers to a large variation of thermal stress.

The main factors that affect human thermal balance are the environment (ambient temperature, radiant temperature, wind and humidity), exercise (duration, intensity and type) and clothing (Fig 1) (Mäkinen, 2006). Clothes protect against conductive and convective heat loss and reduce the exposure of the sun (McArdle et al., 2007). The thermal balance of the human body depends also on individual factors like gender, fitness level, adaption to cold and hot environments and body size. The effective ambient temperature a human is exposed to during activity depends not only on the ambient temperature, but also on the amount of wind, and the velocity of the movement (McArdle et al., 2007).

Rectal temperature (T_{re}) is a measure of core temperature. Core temperature is approximately 37 ºC in a resting human, but rises during physical activity and fatigue generally coincides between core temperatures of 38-40 ºC (McArdle et al., 2007). The rise in core temperature during physical activity is a well-regulated process in the human body, which ensures optimal physiologic and metabolic functions and is found to be proportional to the relative workload (Saltin et al., 1968). It seems that the rise in core temperature is independent of the ambient temperature during moderate and high intensity exercise (Layden et al., 2002).

Skin temperature varies on different places of the body, more distal parts are cooler than central places on the body. A commonly used way to express the overall skin temperature is the weighted mean skin temperature (MST) (Blatteis, 1997). In a study by Layden et al. (2002) with cycling in various ambient condition (20 ºC, 10 ºC, 0 ºC and -10 ºC), MST was found significantly different between different ambient temperatures and that MST decreased despite an increased core temperature.

Skin temperature measurements is an indirectly measure of muscle temperature (Oksa et al., 1997). The findings of Bergh and Ekblom (1979) indicate an optimal endurance performance at muscle temperature at (38.5 ºC). Low muscle temperature results in a lower endurance, force and power performance of the muscle (Oksa, 2002).

In addition to the regularly oxygen demand of the working muscle during exercise, blood is redistributed from the core to the periphery for heat loss during exercise in the heat. This gives the circulation system an extra challenge during exercise in the heat. The increased blood flow to the skin increases skin temperature, thereby ensuring heat loss by conduction, convection, radiation and evaporation of sweat (Gisolfi and Wenger, 1984). This results in an increased heart rate (HR) and sweat loss during physical activity in warm environments (Saltin et al., 1968, Claremont et al., 1975). Increased sweat loss may also induce dehydration, which can impair work performance (Greenleaf, 1992). In cold environments a vasoconstriction of the peripheral vessels will occur to maintain the blood in the core, and to ensure a constant core temperature, thereby resulting in lower skin temperatures. In colder ambient temperatures, aerobe endurance performance can be impaired because of a lower than optimum superficial muscle temperature, that might affect the oxidative enzymes of nerve and muscle cells (Patton and Vogel, 1984). Humans can become more tired and experience loss of moral in cold compared to moderate temperatures (Pugh, 1967). The endurance capacity during cold exposure can also be impaired by frost-bite (Faulkner et al., 1981).

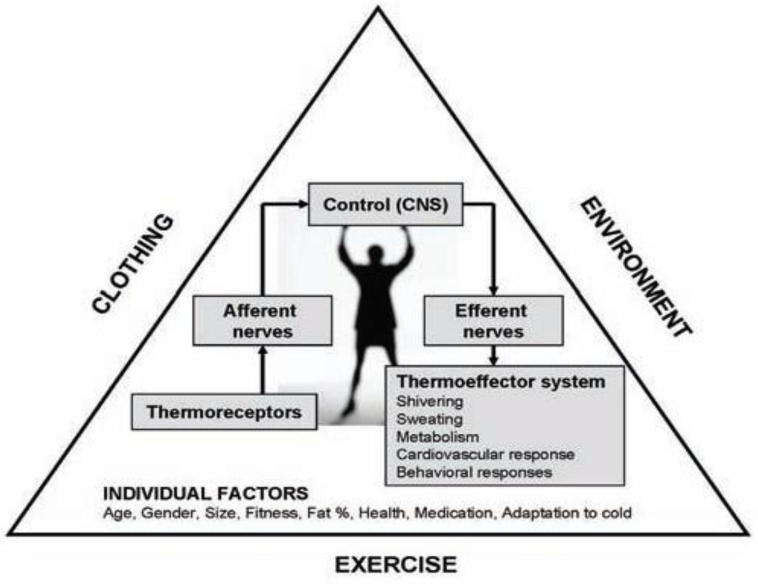

Fig. 1. The human thermoregulatory system and main factors affecting thermal balance (Mäkinen, 2006).

Aerobe endurance performance can be defined as the "*ability to perform large-muscle, whole body exercise at moderate to high intensities for extended periods of time*" (Pate and Kriska, 1984). The physiological parameters as decide the human aerobe endurance performance are maximal aerobic power, anaerobic threshold and work efficiency (Pate and Kriska, 1984). Several studies have investigated aerobe endurance performance in different ambient temperatures and have based their results on 1-3 of the aforementioned physiological parameters in addition to the time to exhaustion (TTE) (Quirion et al., 1989, Galloway and Maughan 1997, Sandsund et al., 1998). An impaired aerobe endurance performance has been reported for cold environments (-15 ºC and -20 ºC) (Quirion et al., 1989, Sandsund et al., 1998), as well as in warm environments (24 ºC and 31ºC) (Kruk et al., 1991, Rowland et al., 2008). Different results are found on ambient temperatures affect on maximal oxygen consumption (VO_{2max}). Some studies reported that VO_{2max} did not vary between different ambient temperatures (Flore et al., 1992, Sandsund et al., 1998). On the other hand, some studies reported a higher VO_{2max} in the heat (20 ºC) (Quirion et al., 1989), or a higher peak oxygen consumption in cold temperatures (-2 ºC) (Therminarias et al., 1989). Of those studies that have investigated a range of ambient temperatures including cold, moderate and warm ambient temperatures, it is reported that the optimal temperature area for aerobe endurance performance lies within moderate temperatures ranging from 3 -11 ºC (Galloway and Maughan 1997, Parkin et al., 1999, Sparks et al., 2005). However, no studies have investigated the effect of both cold and warm exposure in cross country skiers with the same outfit in all the investigated temperatures. The purpose of this study was to investigate the effects of exposure to cold and warm environments on performance-related variables in cross country skiers, wearing standardized skiing clothing.

Since the clothing used in this study is warmer than the clothing used in the forementioned studies, we assumed the optimal ambient temperature area for endurance performance to be at colder temperatures than the previous reported 3-11 ºC. We hypothesized that going from high to low ambient temperatures, MST will gradually decrease despite increasing T_{re}. In addition we hypothesized that the optimal ambient temperature for aerobe endurance performance with the existing cross country skiing suit will be at neutral temperatures around 0 ºC.

Methods

Subjects

Nine highly trained male endurance athletes participated in this randomized study. The mean (±SD) physical characteristics of the subjects were: 25 (±3.2) year of age, 78.6 (±7.4) kg body mass, 11.9 (±2.3) % body fat and 5.6 (±0.4) $L \cdot min^{-1}$, 71.3 (±4.1) $ml \cdot kg^{-1} \cdot min^{-1}$ or 212.3 (±9.1) $ml \cdot kg^{-0.75} \cdot min^{-1}$ VO_{2max}. The subjects were recruited from a college cross country skiing team and a college orienteering team. Inclusion criteria were; age between 20-30 years, $VO_{2max} \geq 60\ ml \cdot kg^{-1} \cdot min^{-1}$ and had an approved medical examination by a physician. Illnesses like flu, exercise-induced asthma and Reynaud syndrome were exclusion criterions. Exclusion criterions during test were $T_{re} \geq 39.5$ °C, skin temperature lower than 10 °C for more than 20 minute continuously at one of the measurement places, or skin temperature lower than 8 °C at one of the measurement places, or that subjects wanted to abort the test. The study was approved by the regional committee for medical research ethics, Central Norway.

Experimental protocol

Each subject completed seven exercise tests that consisted of running on a treadmill (PPS 55 sport-l climatel, Woodway, Weil am Rhein, Germany, accuracy ±0.1 $km \cdot h^{-1}$) in a climatic chamber. First, the subjects performed a pre-test wearing shorts and t-shirt at 20 °C to define VO_{2max} and to get familiar with the test procedure. The results of the pre-test were used to define the intensity for the exercise protocol in the main tests. The six main tests consisted of running on a treadmill with an inclination of 10.5% and a wind speed at 5.5 $m \cdot sek^{-1}$ under varying ambient temperatures (-15 °C, -10 °C, -5 °C, 0 °C, 10 °C, 20 °C). The relative air humidity was set to 50 % at 10 °C and 20 °C, in the four other temperatures it could not be regulated. Ambient temperature and air humidity were measured at the start of, warm up phase, each step during the submaximal phase and maximal phase of the test (Testo435, Testo, Lenzkirch, Germany, accuracy ±0.3 °C). In the present study, the two coldest investigated ambient temperatures -15 ºC and -10 ºC will be mention as cold temperatures, -5 ºC and 0 ºC as neutral temperatures and 10 ºC and 20 ºC as warm temperatures. Each subject performed the tests at same time of the day and with a minimum of 48 hours between each test. The subjects were asked to avoid training before the test each day and to maintain the same training routine the day before each test. The subjects responded before each test to a question schema about their diet, sleep and training habit, to ensure that this was approximate equally each time.

Immediately prior to and after each test, the subjects were weighted in order to register loss of body weight during test (ID1, Mettler Tolledo, Albstadt, Germany, accuracy ±0,006 kg). Following, each subject inserted self the rectal probe 10 cm into rectum, for measurement of T_{re} (YSI 400, Yellow Springs Instruments, Ohio, USA, accuracy ±0.15 °C). For measurement of skin temperatures, skin thermistors (YSI 400,Yellow Springs Instruments, Ohio, USA, accuracy ±0.15 °C) were attached at 13 different places: forehead, neck, left chest, left stomach, back, left upper arm, left lower arm, left palm, left long finger, right anterior thigh, right posterior thigh, left anterior calf and left posterior calf. A heart-rate recorder (Polar $S810^{TM}$ Electro OY, Kempele, Finland, accuracy ± 2 $beats \cdot min^{-1}$) was attached to continuously measure HR during test. The subjects put on the standardized set of clothing before each test as started with a 20 min pre-exercise rest period with the subject sitting in a room at 23 °C. This was performed to stabilise body temperature and HR before the start of exercise. At the end of the pre-exercise rest period, blood lactate concentration ($[La^{-1}]_b$) was measured (Lactate Pro, Arkray, Kyoto, Japan). Lactate Pro has been validated separately, found accurate, reliable and useful for experiment (Medbø et al., 2000). The subjects were also asked to rate their perceived thermal sensation, by using an 11- point scale ranging from -5 (extremely cold) to 5 (extremely warm), where 0 is neutral. After the pre-exercise rest period, the subjects had 10 minutes to put on shoes, the extra pair of trousers and jacket, cap, gloves, wool mittens and buff. One minute before the start of exercise, the subjects went into the climatic chamber.

The exercise test had three phases, a warm up, a submaximal phase and a maximal phase (Fig. 2). The warm up phase consisted of 10 minutes running at 60% of VO_{2max} followed by a six-minute break to measure lactate, and to take off the extra pair of trousers and the jacket. During this period perceived thermal sensation and perceived strain were measured. Perceived strain was registered with subjects responding on Borg scale, which is a 15- point scale from 6 (very easy) to 20 (total exhaustion). The submaximal phase of the test, consisted of running on a treadmill with four steps on 5 minutes with an ascending load on 0,5-1 $km \cdot h^{-1}$ for each step, to define lactate threshold. Intensity was set to 65% of VO_{2max} at the first step and increased with approximately 10% for each step to become 95% of VO_{2max} at the last step. There was a two minutes break between each step, to take a blood sample from the fingertip, to determinate $[La^{-1}]_b$ and to register perceived strain. T_{re}, skin temperatures, HR and oxygen consumption (Oxycon Pro, Jaeger, Hoechberg, Germany, accuracy ±0.05 $L \cdot min^{-1}$) were recorded continuously during each step. After the last step, there was a six minutes break to measure $[La^{-1}]_b$ and register perceived strain and the perceived thermal sensation. The maximal phase of the tests was to define VO_{2max} and TTE by running on the treadmill with increasing load at 1 $km \cdot h^{-1}$ each minute until exhaustion. The subjects were encouraged to push themselves to exhaustion through cheering. Oxygen consumption and HR were recorded during the whole maximal phase. A blood test was taken after completion of the test to define the level of blood lactate. After the max test the perceived thermal sensation and perceived strain were determined.

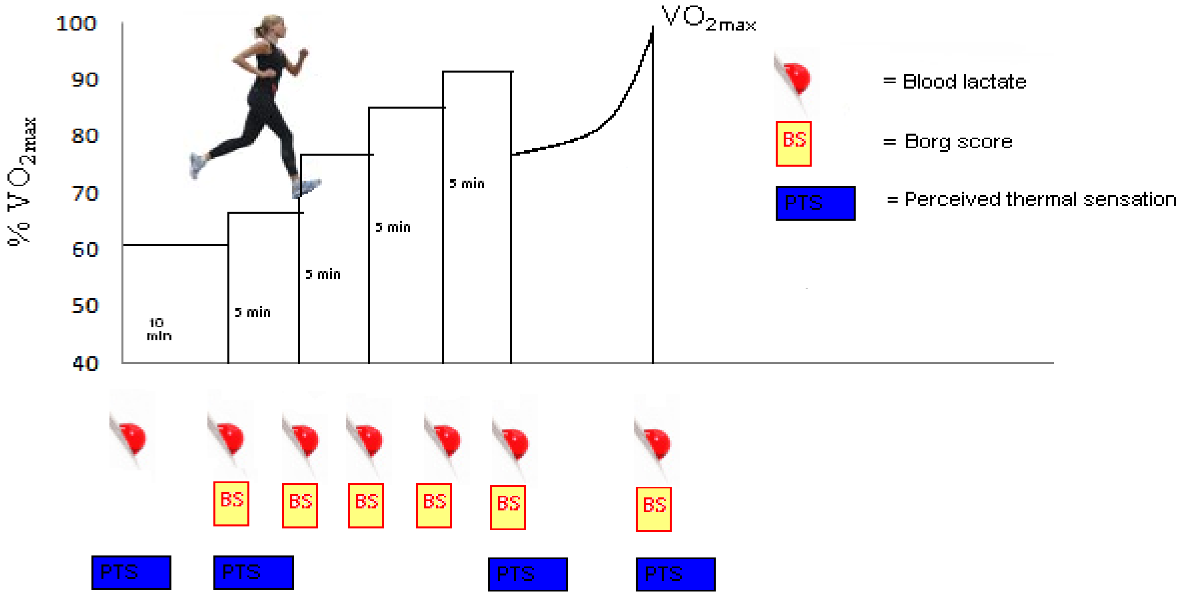

Fig.2. Exercise test protocol.

Clothing

The subjects were dressed in windboxer, socks, underwear, cross country skiing suit, cap and gloves. An extra pair of trousers and a jacket was worn during the warming up phase. Thermal isolation for the underwear and cross country skiing suit was together 1.32 Clo. In addition to the standard clothing, wool mittens and buff were added during the tests at -15 °C, -10 °C, -5 °C and 0 °C. These were added to avoid extremely cold skin temperatures. In addition to the subject self, the clothes were also weighted before and after test (Sartorius AG, Sartorius, Goettingen, Germany, accuracy ±0.01g).

Data analysis

The average values of the last two minutes of the warming up and the four interval steps were used for statistical analysis on submaximal oxygen consumption (VO_2), HR, T_{re} and MST. To define VO_{2max}, maximal minute ventilation (VE_{max}) and highest peak heart rate (HR_{peak}), the average of the two consecutive highest values during the max test were used. TTE was the time from the start of the max test until termination of the max test. MST was calculated as: 0.149*T forehead, 0.186* T left Chest, 0.186* T back, 0.107* T left upper arm, 0.186* T right anterior thigh, 0.186* T right posterior thigh (Teichner, 1958).Lactate threshold was defined as the level when lactate reached a level of 1.5 $mmol \cdot L^{-1}$ above the resting level defined as the average value of the rest and warm up phase (modified version of Helgerud et al., (1990)).

Statistical design

QQ-plots supported the assumption of normally distributed data. General linear model ANOVA for repeated measurements two-ways analysis of variance was used to analyse the development within and between the ambient temperatures on the physiological parameters (MST, T_{re}, VO_2, $[La^{-1}]_b$ and HR). A one-way ANOVA was used to analyse the difference between the different ambient temperature on the physiological parameters (TTE, running speed at lactate threshold, $VO_{2max,}$ HR_{peak} and body mass loss). A Friedman test was used to analyse the development in perceived thermal sensation during the test within the different temperatures. A Wilcoxon test was used to analyse the differences between the ambient temperatures on perceived thermal sensation and perceived strain. Data is presented as mean ± standard derivation (SD) and differences were considered significant if $P<0.05$.

Results

General characteristics of the tests

The ambient temperature at the pre-test was 20.0 °C (±0.1). Ambient temperature at the pre-exercise rest period was 22.7 °C (±0.5). Ambient temperature, humidity, and wind speed in the main tests are shown in table 1. These exactly ambient temperatures are round of and used further away in this paper. The exercise intensity of the submaximal phase was 60 % (±2) of VO_{2max} at the warm up phase, and were 67 % (±5 %), 77 % (±6 %), 85 % (±2 %) and 91 % (±6 %) of VO_{2max}, respectively in the first, second, third and fourth step.

General response to the exercise protocol

Fig. 3 A-D shows the results of the exercise protocol at one of the investigated ambient temperatures (1 °C) for some of the investigated variables. At this ambient condition MST decreased when the subjects entered the climatic chamber after 30 minutes, despite increased work load during (Fig. 3A). On the other hand, T_{re} increased during the test (Fig. 3B).VO_2 (Fig. 3C) and HR (Fig 3D) increased linearly from low to high exercise intensity, and increased at each step during the submaximal phase.

Table 1. Ambient temperature, relative humidity and wind speed during the main tests.

Ambient temperature (°C)	Relative humidity (%)	Wind ($m \cdot sec^{-1}$)
-13.5 ±0.2	45 ±10	5.5
-8.6 ±0.1	29 ±7	5.5
-3.6 ±0.1	20 ±6	5.5
0.8 ±0.2	18 ±4	5.5
9.9 ±0.1	47 ±2	5.5
19.9 ±0.1	49 ±1	5.5

Data are mean values (±SD).

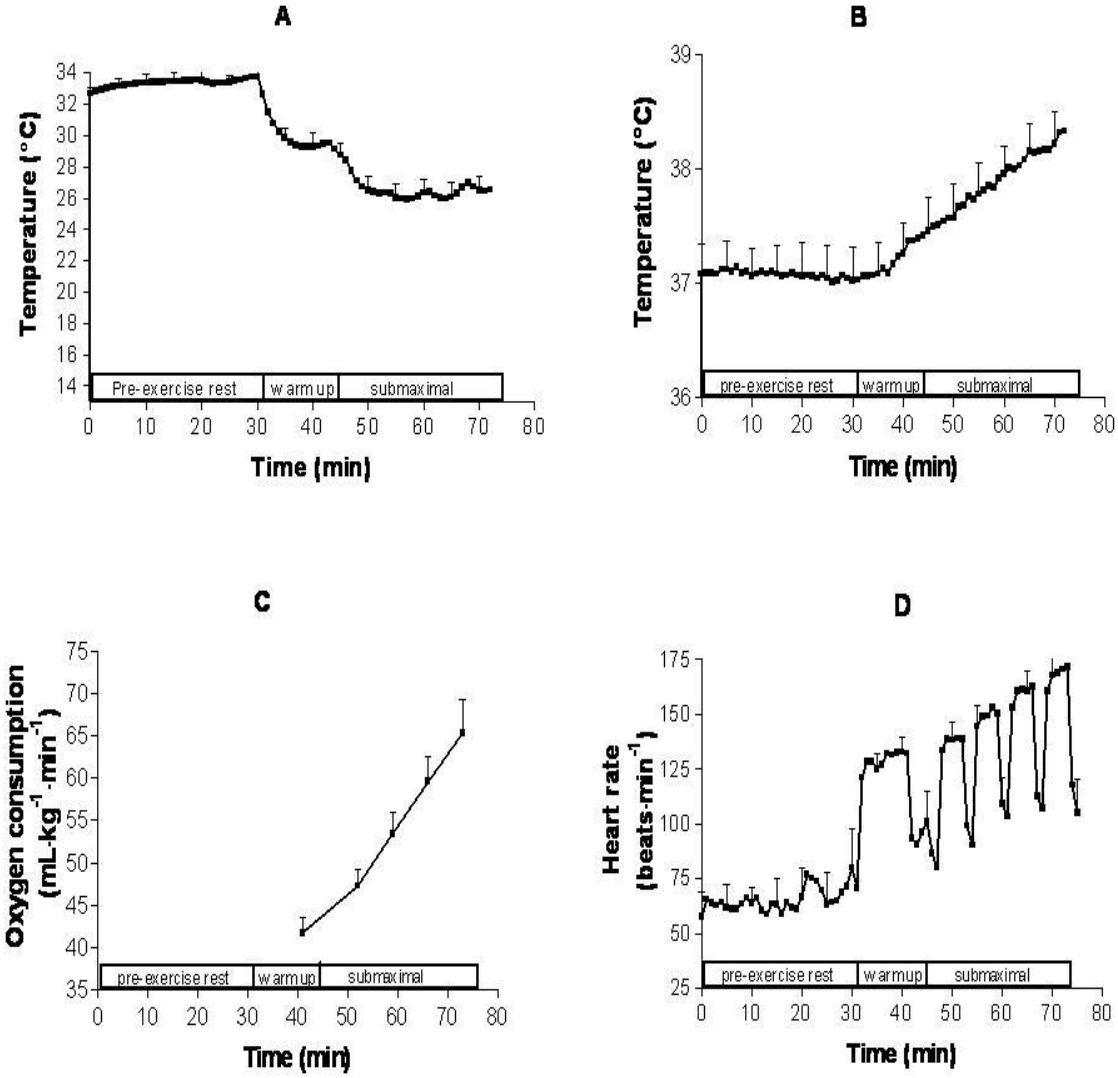

Fig.3. Mean values at 1 °C for: A; Mean skin temperature, B; Rectal temperature, C; Submaximal oxygen consumption, D; Heart rate. SD is shown each fifth minutes.

Effect of ambient temperature on body temperature

Skin temperature

At the end of the submaximal test the highest MST was measured at 20 ºC (32 ºC) and decreased with lower ambient temperature. At -4 ºC and -14 ºC the MST was 7 ºC and 11 ºC lower than at 20 ºC. A significantly difference was found between all ambient temperatures (Fig. 4).

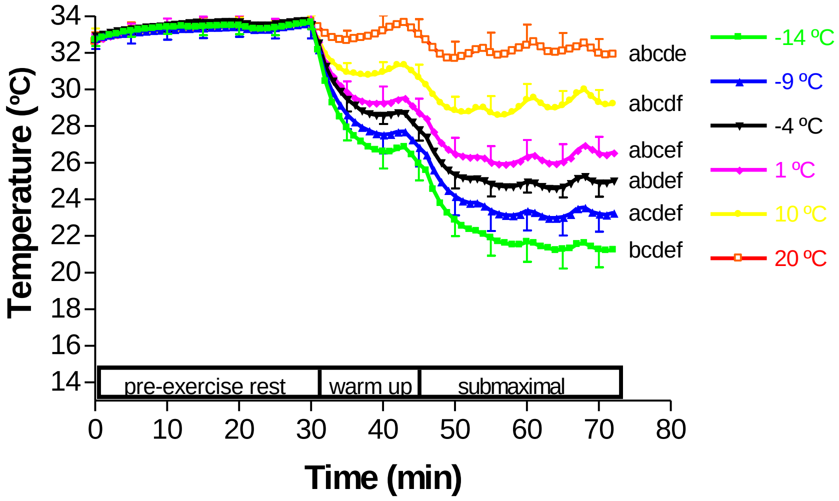

Fig.4. Mean values in mean skin temperature (MST) during all six investigated ambient temperatures. SD is shown each fifth minutes. N= 9; a, b, c, d, e, f indicate a significant difference (P<0.05) from corresponding values at -14 ºC, -9 ºC, -4 ºC, 1 ºC, 10 ºC and 20 ºC, respectively.

At the end of the submaximal phase, the temperature of the anterior (30.4 ºC) and posterior (31.0 ºC) thigh were both highest at 20 ºC and decreased significantly with lower ambient temperature (except between posterior thigh at -14 ºC and -9 ºC). The lowest anterior (17.5 ºC) and posterior (21.3 ºC) thigh temperature was measured at -14 ºC. It was a significant lower anterior thigh temperature compared with posterior thigh temperature at -14 ºC, -9 ºC, -4 ºC and 1 ºC (Fig. 5 and 6).

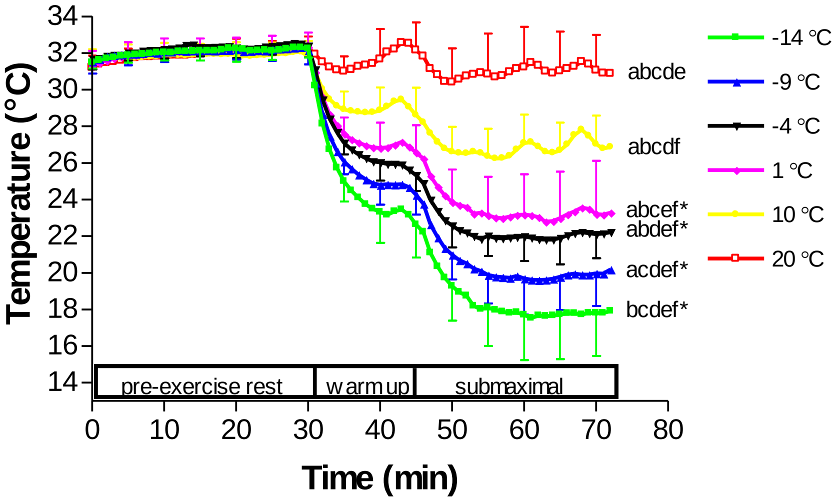

Fig.5. Mean values of anterior thigh temperature during all six investigated ambient temperatures. SD is shown each fifth minutes. N= 9; a, b, c, d, e, f indicate a significant difference (P<0.05) from corresponding values at -14 °C, -9 °C, -4 °C, 1 °C, 10 °C and 20 °C, respectively. * indicate a significant difference (P<0.05) between anterior and posterior thigh at the corresponding ambient temperatures.

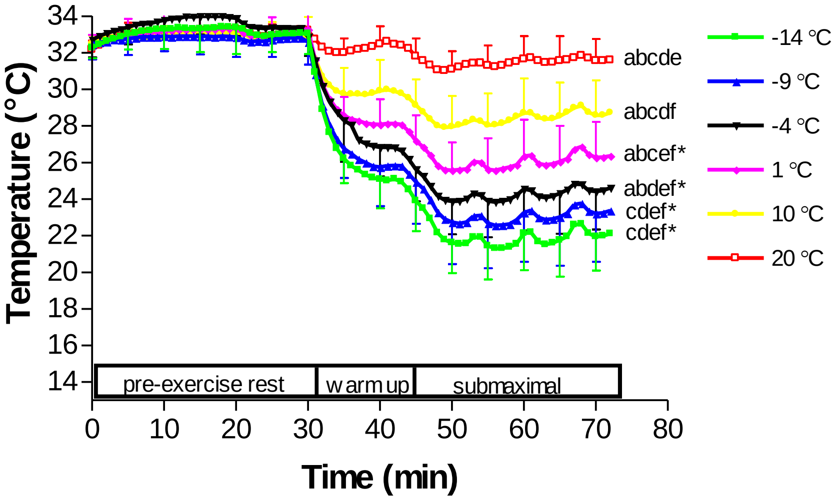

Fig.6. Mean values of posterior thigh temperature during all six investigated ambient temperatures. SD is shown each fifth minutes. N= 9; a, b, c, d, e, f indicate a significant difference (P<0.05) from corresponding values at -14 °C, -9 °C, -4 °C, 1 °C, 10 °C and 20 °C, respectively. * indicate a significant difference (P<0.05) between anterior and posterior thigh at the corresponding ambient temperatures.

Rectal temperature

At the end of the pre-exercise rest period, a stable T_{re} between 37.0 ºC and 37.2 ºC was measured at all ambient temperatures. During the submaximal test the T_{re} rose to 38.5 ºC at the end of the test at 20 ºC. T_{re} was significantly lower in -14 ºC (37.9 ºC) as compared to -9 ºC and 20 ºC (Fig. 7).

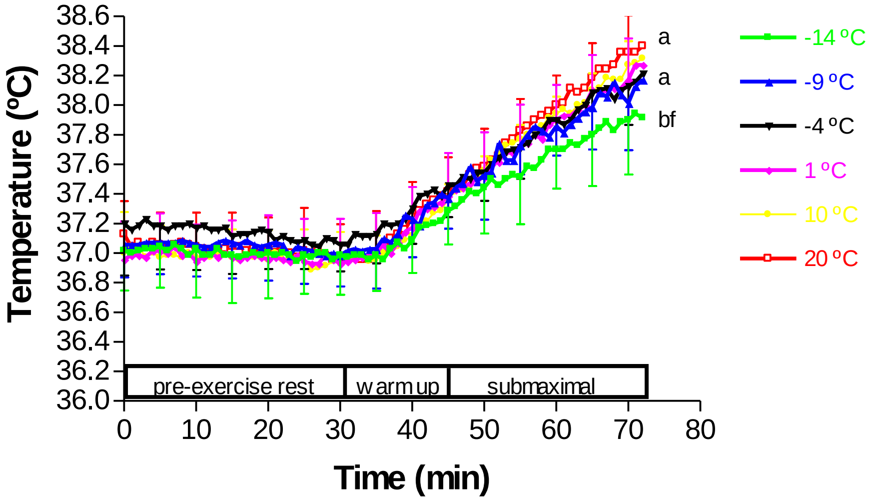

Fig. 7. Mean values in rectal temperature during test for all six investigated ambient temperatures. SD is shown each fifth minutes. N= 7; a, b, c, d, e, f indicate a significant difference (P<0.05) from corresponding values at -14 ºC, -9 ºC, -4 ºC, 1 ºC, 10 ºC and 20 ºC, respectively.

Effect of ambient temperature on aerobe endurance performance

Time to exhaustion

TTE was significant longer at -4 ºC and 1 ºC compared to -14 ºC, 10 ºC and 20 ºC. The shortest time to exhaustion was found at 20 ºC. At -4 ºC TTE was 22.0% longer compared to 20 ºC and 13.4% longer compared to -14 ºC (Fig. 8).

Oxygen consumption

The VO_2 increased linearly from the warm up phase and through the four submaximal steps. The highest VO_2 was found at 10 ºC and 20 ºC, and was significantly higher at 20 ºC, compared with -14 ºC, -9 ºC, -4 ºC and 1 ºC (Table 3). VO_2 did not differ between the four lowest ambient temperatures.

During the maximal phase of exercise there was no significant differences in VO_{2max} between the six investigated ambient temperatures (Table 2).

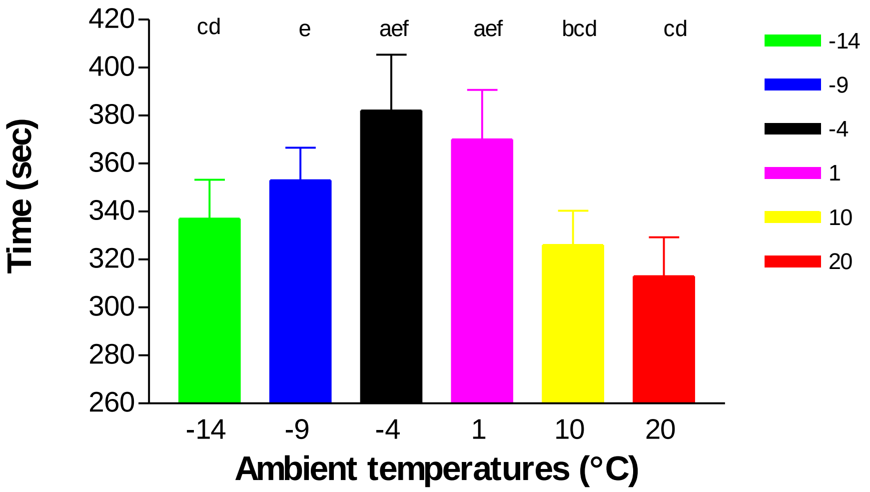

Fig.8. Mean values (±SD) for Time to exhaustion (TTE) for all six investigated ambient temperatures. N= 7; a, b, c, d, e, f indicate a significant difference ($P<0.05$) from corresponding values at -14 ºC, -9 ºC, -4 ºC, 1 ºC, 10 ºC and 20 ºC, respectively.

Blood lactate

Running speed at lactate threshold was highest at -4 ºC (10.1 km·h^{-1}) and was significantly higher compared with -9 ºC (4.3%), 10 ºC (3.0%) and 20 ºC (3.0%) (Table 2).

The $[La^{-1}]_b$ values after the fourth submaximal step was highest at -14 ºC (4.2 mmol·L^{-1}), 10 ºC (4.3 mmol·L^{-1}) and 20 ºC (5.2 mmol·L^{-1}) and lowest at -4 ºC (3.3 mmol·L^{-1}). A significant difference was found between 20 ºC and 10 ºC and -4 ºC, respectively (Table 3).

No significantly difference at highest peak $[La^{-1}]_b$ value at VO_{2max} test between the six investigated ambient temperatures were registered (Table 2).

Heart rate

During the warm up and the four submaximal steps, the HR was significantly higher at 20 ºC than at -14 ºC, -9 ºC, -4 ºC and 1 ºC, respectively (Table 3).

The highest peak HR during the test was at 20 ºC (180 beats·min^{-1}), and was significantly higher than the other temperatures. HR_{peak} was 5.5% and 4.4% higher at 20 ºC compared with -14 ºC and -4 ºC (Table 2).

Effect of ambient temperature on body mass loss

The loss of body mass was significantly higher during the test at 20 ºC, compared to the other ambient temperatures (Table 2). The body mass loss was 151% greater at 20 ºC compared to -14 ºC, and 109% greater than at -4 ºC.

Effect of ambient temperature on subjective measurements

Perceived strain

No significant differences were found in perceived strain between ambient temperatures at exhaustion (Table 2).

Perceived thermal sensation

At the end of the pre-exercise rest period the perceived thermal sensation was “neutral”. After the submaximal and maximal phase of the test, subjects voted themselves as “warm” at 20 ºC, as was significantly higher than all the others ambient temperatures. At -14 ºC subjects voted themselves as “cold”, as was significantly lower than -4 ºC, 1 ºC, 10 ºC and 20 ºC (Fig. 9).

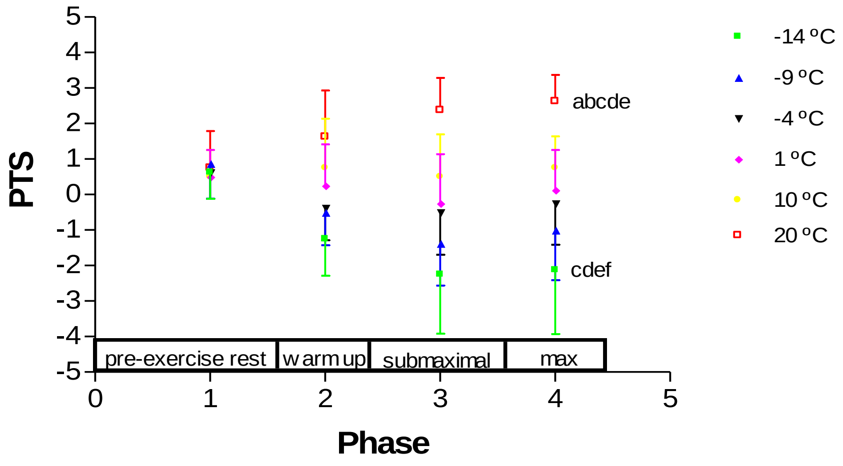

Fig.9. Mean values (±SD) for perceived thermal sensations (PTS) after the pre-exercise rest period, warm up, submaximal and maximal phase. N=8; a, b, c, d, e, f indicate a significant difference (P<0.05) from corresponding values at -14 ºC, -9 ºC, -4 ºC, 1 ºC, 10 ºC and 20 ºC, respectively. The scale range; -5 is extremely cold, 0 is neutral and 5 is extremely warm.

Table 2. Results from the submaximal and maximal part of the tests at the six investigated ambient temperatures.

	-14 ºC	-9 ºC	-4 ºC	1 ºC	10 ºC	20 ºC	N
VO_{2max} (L·min^{-1})	5.6±0.3	5.6±0.3	5.8±0.3	5.8±0.3	5.7±0.2	5.6±0.2	7
VO_{2max} (mL·kg^{-1}·min^{-1})	70.0±4.9	69.8±5.1	71.7±4.1	72.1±4.3	70.4±5.7	70.0±4.7	7
HR_{peak} (beats·min^{-1})	181±7 ef	182±5 ef	183±7 f	186±8 f	187±5 abf	191±6 abcde	5
Running speed at LT (km·h^{-1})	9.8±0.5	9.8±0.4 c	10.1±0.4 bef	10.0±0.5	9.7±0.4 c	9.7±0.5 c	6
$[La^{-1}]_{b\ max}$ (mmol·L^{-1})	8.1±1.4	7.9±1.1	8.7±2.2	8.3±1.8	8.2±1.4	9.2±1.9	8
Ve_{max} (L·min^{-1})	165±13 def	170±9 e	177±17	177±16 a	178±9 ab	180±19 a	7
Body mass loss (kg)	0.5±0.1 cdef	0.5±0.2 ef	0.6±0.1 aef	0.7±0.1 aef	1.0±0.3 abcdf	1.2±0.2 abcde	8
BorgScale	19±1	19±1	19±1	19±1	19±1	19±1	8

Data are mean (±SD). $VO_{2max,}$ maximal oxygen uptake; HR_{peak}, peak heart rate; Running speed at LT, Running speed at lactate threshold; $[La^{-1}]_{b\ max,}$ maximal blood lactate consentration; $Ve_{max,}$ maximal minute ventilation; N, number of subjects; a, b, c, d, e, f indicate a significant difference (P<0.05) from corresponding values at -14 ºC, -9 ºC, -4 ºC, 1 ºC, 10 ºC and 20 ºC, respectively.

Table 3. Results from the warm up and submaximal part of the test at the six investigated ambient temperatures.

Ambient temperature	Exercise steps	VO_2 ($L\cdot min^{-1}$) (N=9)	VO_2 ($mL\cdot kg^{-1}\cdot min^{1}$) (N=9)	HR ($beats\cdot min^{-1}$) (N=6)	$[La^{-1}]_b$ ($mmol\cdot L^{-1}$) (N=9)
-14 ºC		f	f	f	
	Warm up	3.42 ± 0.42	43.3 ± 2.6	133 ± 10	1.3 ± 0.4
	1	3.81 ± 0.47	48.3 ± 2.8	137 ± 13	1.5 ± 0.5
	2	4.15 ± 0.58	52.5 ± 3.8	149 ± 12	1.8 ± 0.7
	3	4.63 ± 0.67	58.5 ± 4.6	159 ± 12	2.4 ± 0.9
	4	5.06 ± 0.55	64.2 ± 4.1	168 ± 10	4.2 ± 1.4
-9 ºC		ef	ef	ef	
	Warm up	3.29±0.38	41.7 ± 2.2	132 ± 10	1.3 ± 0.4
	1	3.7±0.41	46.9 ± 2.7	137 ± 10	1.5 ± 0.3
	2	4.16±0.40	52.9 ± 2.6	148 ± 11	1.6 ± 0.6
	3	4.65±0.48	59.0 ± 2.7	158 ± 11	2.6 ± 1.0
	4	5.12±0.41	65.2 ± 3.9	168 ± 9	3.8 ± 1.4
-4 ºC		e	ef	ef	f
	Warm up	3.33±0.35	42.3 ± 1.5	131 ± 10	1.6 ± 0.6
	1	3.73±0.36	47.4 ± 1.6	136 ± 11	1.2 ± 0.3
	2	4.2±0.41	53.5 ± 1.9	146 ± 12	1.5 ± 0.5
	3	4.7±0.44	59.8 ± 2.7	156 ± 12	2.1 ± 0.8
	4	5.15±0.37	65.7 ± 3.3	166 ± 10	3.3 ± 1.2
1 ºC		ef	ef	f	
	Warm up	3.28±0.36	41.7 ± 1.8	133 ± 8	1.3 ± 0.4
	1	3.72±0.42	47.3 ± 1.9	139 ± 10	1.4 ± 0.4
	2	4.2±0.46	53.4 ± 2.5	151 ± 10	1.7 ± 0.6
	3	4.68±0.46	59.6 ± 2.9	161 ± 10	2.4 ± 1.0
	4	5.11±0.44	65.3 ± 3.9	171 ± 8	3.6 ± 0.9
10 ºC		bcd	bcd	bcf	f
	Warm up	3.48±0.34	44.1 ± 2.2	138 ± 5	1.2 ± 0.3
	1	3.84±0.36	48.6 ± 2.1	143 ± 6	1.2 ± 0.3
	2	4.36±0.40	55.2 ± 2.9	155 ± 7	1.6 ± 0.6
	3	4.85±0.44	61.4 ± 3.3	166 ± 7	2.6 ± 1.1
	4	5.28±0.40	67.0 ± 4.4	175 ± 6	4.3 ± 1.4
20 ºC		abd	abcd	abcde	ce
	Warm up	3.43±0.41	43.5 ± 1.9	139 ± 8	1.3 ± 0.3
	1	3.89±0.42	49.4 ± 1.9	146 ± 10	1.4 ± 0.4
	2	4.38±0.48	55.6 ± 2.1	159 ± 9	1.8 ± 0.5
	3	4.85±0.49	61.6 ± 1.8	170 ± 8	3.0 ± 1.2
	4	5.24±0.44	66.7 ± 2.9	180 ± 7	5.2 ± 1.6

Data are mean (±SD). $VO_{2,}$ submaximal oxygen consumption; HR, heart rate; $[La^{-1}]_{b,}$ blood lactate consentration; N, number of subjects; a, b, c, d, e, f indicate a significant difference ($P<0.05$) from corresponding values at -14 ºC, -9 ºC, -4 ºC, 1 ºC, 10 ºC and 20 ºC, respectively.

Discussion

The major findings of the present study demonstrated a decrease in MST with reduced ambient temperatures, ranging from 20 ºC to -14 ºC, even though T_{re} increased during all ambient conditions. In addition we found an optimal aerobe endurance performance with the existing cross country skiing-suit at neutral environment (-4 ºC and 1 ºC). Warm (10 ºC and 20 ºC) and cold (-14 ºC and -9 ºC) ambient temperatures impair aerobe endurance performance compared with the neutral temperatures, (-4 ºC and 1 ºC).

Warm environments

In this study we found that aerobe endurance performance was impaired in warm compared with neutral environments, as indicated by poorer performance of TTE, VO_2 and running speed at lactate threshold. There was no difference in $VO_{2max.}$

The findings of the shorter TTE in the warm environments are in line with previous studies of Parkin et al. (1999) and Sparks et al. (2005). Parkin et al. (1999) found a shorter TTE during cycling in the heat (40 ºC) and their conclusion of impaired aerobe endurance performance in the heat was based on a shorter TTE, despite their findings of no difference in VO_2. Galloway and Maughan (1997) did also find a decrease in aerobe endurance performance in the heat (31 ºC), with shorter TTE during bicycling until fatigue. However, they found a lower VO_2 in the heat (31 ºC), compared with the cold (4 ºC). In the present study there was a higher VO_2 in the warm environments (10 ºC and 20 ºC) compared with neutral environments. This indicates that to maintain the same exercise intensity in warm as in neutral environments (-4 ºC and 1 ºC), the working muscles must increase oxygen consumption. Fink et al. (1975) did also find a higher VO_2 in the heat (41 ºC) compared with cold (9 ºC). They explained their results with a local exhaustion in the m. quadriceps and m. hamstrings muscle group during bicycling. Rowell (1974) assumed that higher VO_2 during exercise in the heat was a result of the added cost of increased sweating, pulmonary respiration and circulation. The different findings in VO_2 between studies, may be explained with different exercise protocols and clothing used.

In the present study, a higher $[La^{-1}]_b$ was found after the third and fourth submaximal step in the warm environments compared with -4 ºC. This indicates that lactate accumulation occurred earlier in time when exercising in the warm condition and resulting in a lower running speed at lactate threshold. Bergh et al. (1986) did also find a higher $[La^{-1}]_b$ in the heat (45 ºC) than at 15 ºC. They explained their results with a reduced blood volume at 45 ºC than at 15 ºC, because of the larger sweat loss in the heat. A reduced muscle blood flow because of a larger blood flow to the skin for heat dissipation could also increase lactate values (Rowell 1974). Both these theories may explain the findings of a lower running speed at lactate threshold in the present study.

MST was higher in the warm environments compared to the other ambient temperatures. High MST reduces the temperature gradient between the skin and the ambient temperature, and reduces heat loss by convection, conduction and radiation. In addition to a high MST in the present study, an increased loss of body mass and a higher HR during the tests in the warm compared with the lower ambient conditions was also registered. During the test at 20 ºC, the subject's reported themselves as warm, which is in agreement with the measured skin temperatures and T_{re}. The higher MST in the warm environments are in line with the previous studies comparing exercise in warm and neutral environment (Layden et al. (2002) and Sparks et al. (2005)). Galloway and Maughan (1997) did also find a higher MST, HR and loss of body mass in heat (31 ºC) compared with neutral temperature (11 ºC). In the present study the temperature of the thigh was significantly higher in the warm environments compared with neutral environment. High skin temperature indicates high muscle temperature which is found to increase VO_2 during exercise (Bergh and Ekblom 1979). If the muscle temperature in this study was higher than optimal in the warm environment, it could partly explain the reason of the impaired aerobe endurance performance in the warm environments.

HR_{peak} was 4.4% higher at 20 ºC than at -4 ºC. The increased HR during the test in the warm environments is probably the result of higher requirements of blood flow to the vessels underneath the skin to enhance heat loss from the body the environment. Since the speed of the treadmill was equal at all ambient conditions, the working muscles still require the same amount of blood flow, so the increased blood flow to the vessels will be an additional challenge to the heart. This can lead to a reduced central blood volume and thereby a lower stroke volume (Gisolfi and Wenger 1984). During submaximal exercise the rise in HR can counterbalance the decrease in stroke volume, so cardiac output can maintain the same. If exercise persists and intensity rises, HR achieves its maximum value but stroke volume will still be decreased. The result is a decreased cardiac output as follow to poorer performance in the heat (Gisolfi and Wenger 1984). A higher HR in warm environments is also reported by Kruk et al. (1991) and Parkin et al. (1999).

The increased loss of body mass at 20 ºC corresponded to a loss of 1.8% of the subjects body weight and is a result of increased evaporative and respiratory water loss. Greanleaf (1992) suggested that 1% loss of body mass impair thermoregulation during exercise and results in a decreased in physical work capacity. Dehydration with a 4% loss of body mass is found to reduce stroke volume and cardiac output during exercise in the heat at work loads at 70-72% of VO_{2max} (Gonzalez-Alonso et al., 1997). Craig and Cummings (1966) found that loss of body mass of 1.9% resulted in a 22% decrease in aerobe endurance performance. This is the same as found in the present study with a 22% decrease in TTE at 20 ºC compared with -4 ºC.

Cold environments

In this study we also found that aerobe endurance performance was impaired in the cold compared with the neutral temperatures, as indicated by poorer performance of TTE and running speed at lactate threshold. No significant differences in VO_2 and VO_{2max} between the cold and the neutral ambient temperatures were found.

The shorter TTE in the cold (-14 ºC) supports the results of Patton and Vogel (1984) and Quirion et al. (1989). Patton and Vogel (1984) suggested that the reason for this impaired aerobe performance in the cold was the effect of the cold ambient temperature on the muscle temperature. This was again based on Faulkner (1980) who suggested that cold ambient temperatures affect muscle temperatures to be lower than optimal for activity of oxidative enzymes, for excitability of nerves and muscle and for nerve conduction. In the present study a MST of 21.2 ºC was found at the end of the submaximal phase of the test in the coldest ambient condition (-14 ºC). In the neutral temperature (-4 ºC) the MST was 25 ºC. This was close to the findings of Galloway and Maughan (1997), who reported a MST at approximate 23 ºC in their coldest test (4 ºC) and 25 ºC in the test in the ambient temperature of 11 ºC. Galloway and Maughan (1997) did also find a significant decrease in TTE at (4 ºC) compared with (11 ºC). Even though their ambient conditions were different from our study, almost similar results were found. This can be explained by the different exercise protocols, windchill and clothing used in the two studies. Galloway and Maughan (1997) found a higher VO_2 in the cold (4 ºC) and suggested that mechanical efficiency was altered, causing an impaired exercise performance in the cold. This can not be the reason in the present study where the VO_2 was equal during the tests in the cold (-14 ºC and -9 ºC) and neutral (-4 ºC and 1 ºC) temperatures. The equal VO_2 between cold and neutral ambient temperatures supports the findings of Layden et al. (2002), who found no difference in VO_2 between 0 ºC and -10 ºC.

During cross country skiing and running, the m. quadriceps and m. hamstrings are two of the biggest and most important muscle groups used to ensure effective and good propulsion. In the four coldest ambient conditions that we investigated the temperature of the anterior thigh was significantly lower than the posterior thigh. This is explained by the headwind that cools the front of the body more extensive compared with the back. Wind affect the effective ambient temperature as is based on wind and ambient temperature, so the effective ambient temperature was even colder than the measured ambient temperature during tests. Wind was also the reason for the higher ambient temperature than scheduled during the forementioned tests (-15 ºC was scheduled but the exactly temperature was -14 ºC etc). This occurred because the testing crew had to open the door to the climatic chamber during tests of practical reasons. Makinen et al. (2001) found a significant lower temperature at the anterior thigh during exercise training at -10 ºC with an added wind speed of 5 $m \cdot sek^{-1}$ compared with no added wind. They also found a 6 ºC higher temperature at the anterior thigh compared with posterior. In the present study, anterior thigh temperature was 17.5 ºC at the end of the test at -14 ºC, and was 5 ºC and 6 ºC higher at anterior thigh at the end of the test at -4 ºC and 0 ºC, respectively. Studies have shown that lower skin temperature result in lower muscle temperature which results in poorer performance (Blomstrand et al., 1984, Oksa et al., 1997). Bergh and Ekblom (1979) investigated physical performance during cycling at normal muscle temperature (38.5 ºC) compared with one elevated (39.3 ºC) and two decreased (36.5 ºC and 35.1 ºC) muscle temperatures. They found a significant lower aerobe endurance performance when the muscle temperature was below normal. In the present study, it is possible that the low thigh temperatures have reduced the superficial muscle temperature which can explain the impaired aerobe endurance performance in the cold (-14 ºC) compared with the neutral temperatures. The subject's in the present study reported that they felt cold during the test at -14 ºC, which is in line with the measured skin temperatures and T_{re}. In a Canadian ski marathon the skier's performance was impaired in the cold environment and the skiers reported a cold- induced pain (Faulkner et al., 1981). No pain were reported by the subjects in our study, but the cold feeling during exercise may have a negative effect on performance, with loss of moral (Pugh, 1967).

Running speed at lactate threshold was equal at -14 ºC and -9 ºC, and was significantly lower at -9 ºC than at -4 ºC. Blomstrand et al. (1984) suggested that, higher levels of $[La^{-1}]_b$ are reached with low muscle temperatures. A reduced muscle temperature may change the muscle fibre recruitment from type 1 to type 2 (Rome et al., 1984), which may also increase the lactate production (Weller et al., 1997). Blomstrand and Essen-Gustavson (1987) suggest that the more rapid accumulation of lactate during exercise with reduced muscle temperature is partly a reason for impaired endurance performance. In the present study the results from running speed at lactate threshold were based on a low number of subjects (N=6), a higher number of subjects would probably result in significant different results also between -14 ºC and -4 ºC.

Cold, neutral and warm environments

There was no significant difference in VO_{2max} between the ambient temperatures. This shows that despite a poorer performance in the cold and warm ambient temperatures, VO_{2max} is not altered, but is reached earlier. This is in agreement with earlier findings of Flore et al. (1992) and Sandsund et al. (1998). On the other hand, Quirion et al. (1989) found a higher VO_{2max} in the heat (20 ºC) compared with cold (0 ºC and -20 ºC). They explained their findings with a lower workload and TTE in the cold. Different workloads between ambient temperatures are not possible in the present study, since the test subjects used the same exercise protocol with the same exercise intensity at each test.

T_{re} rose 0.8 ºC - 1.2 ºC at all ambient temperatures. In this study T_{re} was used as a measure of core temperature. High core temperature may be the limiting factor in exercise with heat stress (Nielsen et al., 1993). This was probably not a factor in the present study where the highest T_{re} measured was 38.5 ºC and no significant difference was found between neutral and cold and warm temperatures. This result is in line with the findings off Sparks et al. (2005) as found no significant difference in core temperature between 10 ºC, 20 ºC and 30 ºC.

Limitations

One of the parameters aerobe endurance performance was based on was TTE. In addition to physiological performance, TTE depend on the subject's mental skills to push themselves to exhaustion. This can vary from one test to another, and may influence the result. The subjects were asked about perceived strain after the end of the maximal test and mean values were 19 (very hard) at all ambient temperatures. This indicates that the subjects have pushed themselves to exhaustion equally at all tests. The tests were accomplished over three months, and the subject's daily training diary and physical capacity can be altered over time. To ensure that the trainings schedule would be as equally as possible during the test period, the subject's were not allowed to train the day tests were performed. In addition the tests were randomly performed for each subject. Nine subjects were included in this project. During the tests some loss of data has occurred, due to illness or loss of data during the tests. This has resulted in a low number of subjects for some of the investigated parameters and thereby a significant difference can be hard to find. In the present study skin temperature was measured. Based on the existing knowledge which assumes that skin temperature is an indication of muscle temperature, some of the explanations of impaired aerobe performance in cold and warm environment are based on skin temperature. Measurements of muscle temperature directly would have been preferable. To make the tests as similar to cross country skiing as possible, it would have been an advantage to perform the tests using roller ski on the treadmill.

Practical implications

In the present study the subjects were wearing normal cross country skiing clothing for cold environments at all ambient temperatures. A wind speed at $5.5 \text{m}\cdot\text{sek}^{-1}$ was chosen because it corresponds to the headwind the cross country skiers expose themselves for, during movement velocity in skiing. These two factors make this study relevant for competition and exercise for cross country skiers in different environments. The results of poorer aerobe endurance performance in cold environments may indicate that cross country skiers clothing should be more protective during cross country skiing in cold ambient conditions.

Conclusion

The present study demonstrated a decrease in MST with reduced ambient temperatures, ranging from 20 ºC to -14 ºC, even though T_{re} increased during all ambient conditions. Despite an unaltered VO_{2max}, TTE was longer, VO_2 was lower and running speed at lactate threshold was higher in the neutral environments (-4 ºC and 1 ºC). Warm (10 ºC and 20 ºC) and cold (-14 ºC and -9 ºC) environments impaired aerobe endurance performance. Since the clothing used in the present study is warmer than the clothing used in previous studies in this field of research, the optimal ambient temperature area for endurance performance was found to be at colder temperatures than the previous reported 3-11 ºC. We conclude then, that an optimal aerobe endurance performance with the existing cross country skiing-suit will be at neutral environment (-4 ºC and 1 ºC).

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