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Effect of ambient temperature on female endurance performance

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ABSTRACT

Ambient temperature can affect physical performance, and an ambient temperature range of −4 °C to 11 °C is optimal for endurance performance in male athletes. The few similar studies of female athletes appear to have found differences in response to cold between the genders. This study investigated whether ambient temperature affects female endurance performance. Nine athletes performed six tests while running on a treadmill in a climatic chamber at different ambient temperatures: 20, 10, 1, −4, −9 and −14 °C and a wind speed of 5 m s^{-1}. The exercise protocol consisted of a 10-min warm-up, followed by four 5-min intervals at increasing intensities at 76%, 81%, 85%, and 89% of maximal oxygen consumption. This was followed by an incremental test to exhaustion. Although peak heart rate, body mass loss, and blood lactate concentration after the incremental test to exhaustion increased as the ambient temperature rose, no changes in time to exhaustion, running economy, running speed at lactate threshold or maximal oxygen consumption were found between the different ambient temperature conditions. Endurance performance during one hour of incremental exercise was not affected by ambient temperature in female endurance athletes.

1. Introduction

Some winter sports athletes, such as cross-country skiers, are exposed to a wide range of ambient temperatures (T_a), which can be as high as 10 °C and as low as −20 °C during international competitive events. While solar radiation can increase the heat load on the body, rapid movement increases convective heat loss from the body. Wearing thin racing suits instead of traditional cold-weather clothing decreases protection against heat loss from the body.

The effect of T_a on performance has been widely studied in male subjects. These studies have found impaired endurance performance, measured as time to exhaustion (TTE), in cold (−20 °C and −15 °C) (Quirion et al., 1989; Sandsund et al., 1998) and warm (31 °C) (Rowland et al., 2008) environments compared to more neutral environments (20 °C, 23 °C and 19 °C respectively). A few studies have investigated performance in a wide variety of T_a and have demonstrated that male athletes' optimal performance is achieved between −4 °C and 11 °C (Galloway and Maughan, 1997; Parkin et al., 1999; Sandsund et al., 2012; Sparks et al., 2005) . This temperature range can change according to the clothing worn, wind and relative humidity. Wearing standard cross-country skiing clothing in a gentle breeze, the temperature range for optimal performance for males is −4 °C to 1 °C (Sandsund et al., 2012). T_a have been shown to have an effect not only on TTE, but also on performance-related physiological and metabolic responses, including running economy (Sandsund et al., 2012), running speed at lactate threshold (LT) (Sandsund et al., 2012) and maximal oxygen consumption (VO_{2max}) (Kruk et al., 1991; Oksa et al., 2004; Quirion et al., 1989).

T_a has a strong influence on skin temperature, and skin temperature is believed to indirectly reflect muscle temperature (Blomstrand et al., 1984; Oksa et al., 1997). Women have lower mean skin temperature (T_{skin}) than men when exposed to the same low T_a (Stevens et al., 1987; Walsh and Graham, 1986). Dynamic muscular performance has been shown to be thermally dependent. For each 1 °C increase in muscle temperature, performance is improved by 2–5%; however if central temperature increases (i.e. hyperthermia), this positive relationship reverses and performance is impaired (Racinais and Oksa, 2010). A lower than optimum muscle temperature appears to reduce force and power (Ferretti et al., 1992), reducing muscle performance due to poorer coordination of working muscle groups (Oksa et al., 1997).

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It has been shown that an increase (from ~35 to 38 °C) in muscle temperature increases mechanical efficiency in women during moderate-intensity exercise (Bell and Ferguson, 2009).

According to Graham (1988), there are fundamental differences in how men and women react to cold stress. There are differences between the genders in height, weight and body shape, therefore also in the relationship between surface area and volume. Muscle mass, body fat and fat distribution contribute to differences in body insulation, which in turn influences the rate of heat exchange with the environment. Muscle mass also influences the rate of heat production. Morphological differences may explain some of the differences in heat exchange with the environment between the genders. There also seem to be differences in thermoregulatory responses to cold stress (Graham, 1988; Kaciuba-Uscilko and Grucza, 2001; Stocks et al., 2004). During the luteal phase of the menstrual cycle women have a higher core temperature threshold for the initiation of thermoregulatory response during cold stress (Stephenson and Kolka, 1993). Men respond to cold stress by increasing their metabolism instead of allowing their skin temperatures to cool to the extent that is seen in women (Graham, 1988). Another difference in the response between the genders is a cardiovascular shift, with increased stroke volume and lower heart-rate (HR) in men, but not in women, during cold stress (Stevens et al., 1987).

Since most studies of endurance performance at different T_a have been performed on men, and because there seem to be differences in the response to cold between the genders, the objective of this study was to determine whether T_a also influences female endurance performance, and according to previous studies it appeared that it would be sufficient to test within an ambient temperature range of 20 °C to −14 °C while wearing standard cross-country skiing clothing.

2. Methods

2.1. Subjects

Nine healthy female endurance athletes volunteered to participate in this study. Their mean age was 23 ± 2.9 years, body height 167 ± 6.1 cm, body mass 60.9 ± 7.0 kg, body fat 25 ± 3% and VO_{2max} 3.25 ± 0.46 L min^{-1} (56.2 ± 4.9 ml kg^{-1} min^{-1}). The subjects were informed about the test protocol and their right to withdraw from the experiment according to the Helsinki Declaration before they gave their informed, written consent. The study was approved by the Regional Committee for Medical and Health Research Ethics, Central Norway.

The subjects were recruited from a college cross-country skiing team and a college orienteering team. The inclusion criterion was a VO_{2max} above 45 ml kg^{-1} min^{-1}. Exclusion criteria were earlier cold-related injuries, Raynaud's syndrome and exercise- or cold-induced asthma. These criteria were selected with the aim of obtaining a homogeneous group capable of performing the experimental protocol.

2.2. Overall study design

Several performance and physiological parameters were measured during one hour of incremental exercise under environmental conditions typically encountered by winter sports athletes. The participants visited the laboratory on seven occasions, once pre-test and for six main tests. The pre-test defined VO_{2max} and familiarised the subjects with the test procedure. The results were used to define individual running speed in the exercise protocols for the six main tests. The main tests consisted of a warm-up phase, a submaximal test of four 5-min intervals at increasing velocities, and an incremental test to exhaustion.

With the aim of avoiding any order effects, the main tests were performed in random order at the six T_a of 20 °C, 10 °C, 1 °C, −4 °C, −9 °C and −14 °C (mean T_a and relative humidity; 19.7 ± 0.6 °C, 49 ± 2%; 9.9 ± 0.3 °C, 49 ± 6%; 0.5 ± 0.4 °C, 22 ± 5%; −3.6 ± 0.6 °C, 22 ± 3%; −8.9 ± 0.4 °C, 29 ± 5% and −13.9 ± 0.7 °C, 38 ± 10%) measured after the warm-up, after the four intervals and after the incremental test to exhaustion (Testo435, Testo, Lenzkirch, Germany). A wind velocity of approximately 5 m s^{-1} was produced continuously during the entire test by three fans (total height 189 cm, width 64 cm, BSV, Bergen , Norway) placed approximately 100 cm in front of the subjects. The six tests for each subject were performed at the same time of day (±1 h), with a minimum of 48 h between each test, and in the luteal or quasi-luteal phase of the menstrual cycle. The subjects were instructed to follow guidelines prior to testing that involved avoidance of alcohol for 24 h before testing, consuming coffee, tea or chocolate 2 h before testing and avoiding prior training on the same day as the test. They were also instructed to maintain the same training regime on the day before each test and to complete a short questionnaire about their diet, sleep and training for the test day, in order to ensure that there were no major deviations from test to test.

2.3. Procedures

Before each experiment, the subjects were equipped and dressed in a standard set of commercially available ski clothing comprising a woollen fleece bra, wind-proof boxer shorts, synthetic long-sleeved shirt, synthetic long johns, woollen socks, cross-country racing suit, gloves and hat. During the warm-up period they wore windproof trousers and a jacket, which were removed before the first 5-min interval. In the T_a 1 °C, −4 °C, −9 °C and −14 °C conditions they wore an extra pair of woollen mittens and a head scarf. This was done to maintain finger and neck temperature to avoid drop-outs due to low skin temperatures. They wore their own running shoes during the experiment.

The test started with a 30-min resting period at room temperature (23.7 ± 1.7 °C) to stabilise rectal and skin temperatures. One minute before the start of exercise the subjects entered the climatic chamber, where a warm-up phase of 10 min at an exercise intensity of 71% of VO_{2max} was followed by a submaximal test to define running economy and the LT. The submaximal test consisted of four 5-min intervals at increasing velocities and exercise intensities of 76%, 81%, 85% and 89% of VO_{2max} (Fig. 1). The VO_{2max} was reached and TTE measured after stepwise increments in exercise intensity every minute until exhaustion. The treadmill (PPS 55 sport-l climatel, Woodway, Weil am Rhein, Germany) had a 6° uphill gradient, which was chosen because cross-country skiers tend not to have a running technique that enables them to reach VO_{2max} at low inclination. There was a two-minute pause between each interval of the submaximal test to record the rate of perceived exertion (RPE) and to measure blood lactate concentration ($[La^-]_b$). After the warm-up phase and the submaximal test there was a six-minute pause to record RPE, 6–20 Borg Scale (Borg, 1970), perceived thermal sensation (PTS) using seven-point questionnaires from ISO 7730 (ISO, 2005) and $[La^-]_b$, which were also recorded after the incremental test to exhaustion.

2.4. Measurements

Core temperature was measured continuously as rectal temperature (T_{re}) at 10 cm depth using a thermistor probe (YSI 400, Yellow Springs Instruments, Ohio, USA; ±0.15 °C). Skin temperatures were measured continuously by 13 skin thermistors (YSI

400; ±0.15 °C) positioned on the forehead, neck, chest, abdomen, back, upper arm, lower arm, hand, finger, anterior calf, posterior calf, anterior thigh and posterior thigh. For calculation of the T_{skin} all skin temperatures except finger temperature were used in the calculations, which were modified from Olesen et al. (1972). Oxygen consumption (VO_2) was measured every 20 s when running by indirect calorimetry (Oxycon Pro, Jaeger GmbH, Höchberg, Germany). HR was continuously recorded using a heart-rate monitor (Polar RS800 Polar Electro Oy, Kempele, Finland; ±1 beat min^{-1}). $[La^-]_b$ was determined from a blood sample taken from the fingertip and was analysed using a lactate analyser (Lactate Pro, Arkray, Kyoto, Japan). Lactate threshold (LT) was defined as the intensity at which $[La^-]_b$ reached 1.5 mmol L^{-1} above the average value derived from rest and warm-up values; modified version of Helgerud et al. (1990). Running speed at LT was determined by interpolation (straight lines) between the two closest measured values (Helgerud et al., 1990). To register loss of body weight, subjects were weighed without clothing immediately before and after each test (ID1, Mettler-Toledo GmbH, Albstadt, Germany), and there was no intake of food or water during the tests.

2.5. Statistical analyses

For statistical analyses we used PAWS Statistics 18. QQ-plots were used to test the assumption of normally distributed data. A general linear model (GLM) for repeated measurements was used to analyse the development within and between the ambient temperatures of the physiological variables (T_{skin}, T_{re}, VO_2, $[La^-]_b$ and HR). One-way ANOVA was used to test for differences in TTE, blood lactate concentration after incremental test to exhaustion ($[La^-]_{bmax}$), running speed at LT, running economy, VO_{2max}, maximal heart rate at incremental test to exhaustion (HR_{peak}) and body mass loss between the T_a. To analyse the development between the different T_a, non-parametric data (RPE and PTS) were compared using Friedman's test. Where differences were found between the T_a, a Wilcoxon signed-rank test was used to determine between which T_a the significant differences were to be found. All data are presented as mean ± standard deviation, and differences were considered significant if $P < 0.05$.

Some loss of data during the tests reduced the number of subjects in some of the parameters registered. VO_2 measurements from the tests at −14 °C were eliminated from the data because of a leakage of expired air caused by the freezing of a valve in the mouthpiece.

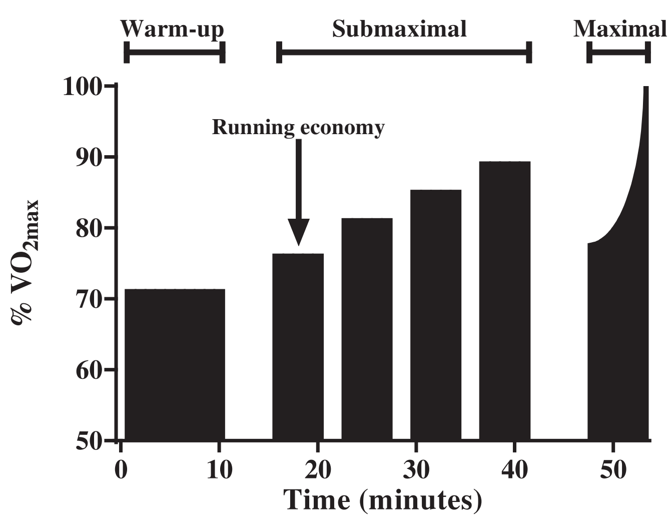

Fig. 1. Schematic representation of the experimental protocol as used in this study.

3. Results

3.1. Aerobic endurance

There were no significant differences in TTE, running economy, running speed at LT or VO_{2max} between the T_a (Table 1).

There was no significant difference in VO_2 during the submaximal test between the T_a.

$[La^-]_{bmax}$ increased with increasing T_a (Table 1). The highest $[La^-]_{bmax}$ was registered at 20 °C and was significantly higher than at −4 °C, −9 °C and −14 °C. $[La^-]_{bmax}$ at 10 °C and 1 °C was significantly higher than at −9 °C and −14 °C. $[La^-]_{bmax}$ at −5 °C was significantly higher than at −14 °C.

During the submaximal test there were no significant differences in HR between the T_a. HR_{peak} increased with increasing T_a. The highest HR_{peak} was registered at 20 °C and was significantly higher than at 1 °C, −4 °C, −9 °C and −14 °C. HR_{peak} at 10 °C was significantly higher than at −4 °C, −9 °C and −14 °C. HR_{peak} at 1 °C was significantly higher than at −9 °C and −14 °C (Table 1).

The largest loss of body mass was at 20 °C, and was equal to 1.1% of total body mass. The body mass loss diminished with falling T_a, and there were significant differences between all T_a, except between −9 °C and −14 °C (Table 1).

Table 1
Results from the submaximal test and the incremental test to exhaustion at the six ambient temperatures (T_a).

	Ambient temperatures						N
	20 °C	10 °C	1 °C	−4 °C	−9 °C	−14 °C	
TTE (s)	297 ± 48	312 ± 50	309 ± 51	312 ± 66	301 ± 37	288 ± 36	9
Running economy (mL kg^{-1} min^{-1})	41.8 ± 2.6	41.5 ± 2.2	42.8 ± 3.9	41.8 ± 3.4	41.6 ± 3.7		9
Running speed at LT (km h^{-1})	7.4 ± 0.8	7.6 ± 0.8	7.5 ± 0.9	7.4 ± 1.0	7.6 ± 0.7	7.7 ± 0.9	7
$[La^-]$ at LT (mmol l^{-1})	3.0 ± 0.4	2.9 ± 0.4	3.0 ± 0.4	3.0 ± 0.4	3.1 ± 0.4	3.0 ± 0.4	9
VO_{2max} (L min^{-1})	3.35 ± 0.43	3.32 ± 0.38	3.36 ± 0.40	3.35 ± 0.47	3.27 ± 0.43		9
$[La^-]_{bmax}$ (mmol l^{-1})	10.4 ± 2.1def	10.0 ± 2.4ef	9.4 ± 3.0ef	9.1 ± 2.4af	7.7 ± 2.0abc	7.2 ± 1.6abcd	9
HR_{peak} (beats min^{-1})	194 ± 10.4cdef	192 ± 10.7def	190 ± 9.7aef	189 ± 8.3ab	187 ± 9.0abc	187 ± 9.3abc	9
Body mass loss (g)	625 ± 71bcdef	500 ± 76acdef	375 ± 89abdef	313 ± 64abcef	238 ± 52abcd	225 ± 46abcd	8
RPE	19 ± 0	19 ± 1	18 ± 1	19 ± 1	18 ± 1	19 ± 1	9
T_{re} after submaximal test (°C)	38.4 ± 0.5	38.7 ± 0.2	38.6 ± 0.1	38.6 ± 0.3	38.5 ± 0.2	38.5 ± 0.2	9

Data are presented as mean ± standard deviation (SD). VO_{2max}, maximal oxygen consumption; TTE, time to exhaustion; $[La^-]$ at LT, blood lactate concentration at lactate threshold; $[La^{-1}]_{bmax}$, blood lactate concentration after the incremental test to exhaustion; HR_{peak}, highest measured heart rate; RPE, rate of perceived exertion; T_{re}, rectal temperature. a, b, c, d, e, and f indicate a significant difference ($P < 0.05$) from corresponding values at 20 °C, 10 °C, 1 °C, −4 °C, −9 °C and −14 °C, respectively.

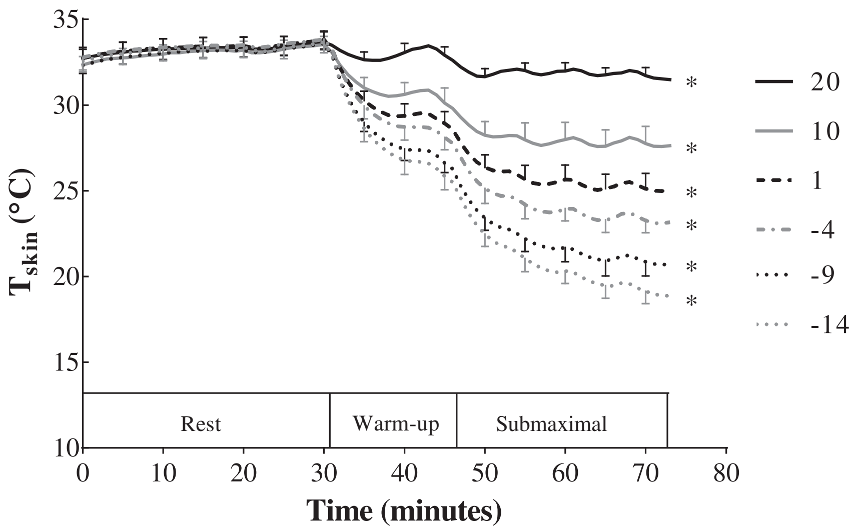

Fig. 2. Mean skin temperature (T_{skin}) at the six ambient conditions. Values are expressed as mean ± SD. Asterik (*) indicates significant ($P < 0.05$) difference from all the other ambient temperatures (T_a).

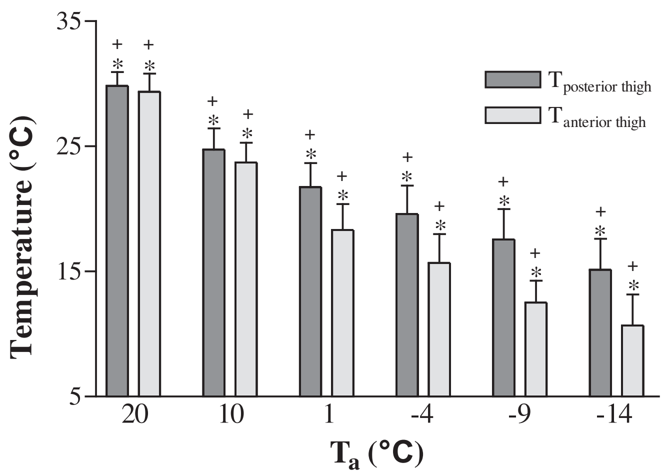

Fig. 3. Skin temperature on the posterior thigh ($T_{posterior\ thigh}$) and the skin temperature on the anterior thigh ($T_{anterior\ thigh}$) at the end of the submaximal test. Values are expressed as mean ± SD. Asterik (*) indicates significant ($P < 0.05$) difference from all the other ambient temperatures (T_a). Plus symbol (+) indicates significant ($P < 0.05$) difference between $T_{posterior\ thigh}$ and $T_{anterior\ thigh}$.

3.2. Core and skin temperature

There were no significant differences in T_{re} between the T_a. T_{re} stabilised at 37.1–37.2 °C at the end of the resting period. As intensity increased, T_{re} rose to between 38.4 and 38.7 °C at the end of the submaximal test (Table 1).

During the resting period T_{skin} stabilised at 33.0–33.5 °C (Fig. 2). At all T_a, T_{skin} fell after the climatic chamber was entered. At the end of the warm-up phase, T_{skin} stabilised at a new and lower level at all T_a. When the subjects removed the extra clothing after the warm-up period, T_{skin} continued to fall at all T_a. At the end of the submaximal test the difference in T_{skin} between the highest (20 °C) and the lowest (−14 °C) T_a was 13 °C, and T_{skin} differed significantly between all ambient conditions (Fig. 3). The highest skin temperatures at the end of the submaximal test on the anterior and posterior thigh were measured at 20 °C to 29.6 ± 1.4 °C and 29.9 ± 1.0 °C and the lowest skin temperatures were measured at −14 °C to 10.8 ± 2.3 °C and 15.2 ± 2.4 °C respectively. Differences of 18.8 °C on the anterior thigh and of 14.7 °C on the posterior thigh were registered between the highest and the lowest T_a (Fig. 3).

3.3. Subjective measurements

The subjects rated their RPE as extremely hard after VO_{2max} at all the T_a (Table 1). PTS on the whole body were reported as neutral after the resting period. Both T_a and the duration of the exposure influenced PTS. The biggest difference in PTS between the T_a was after VO_{2max}. At 20 °C the subjects felt hot and significantly warmer than at the other T_a. At 1 °C and −4 °C they felt neutral, while at −9 °C and −14 °C they felt cold and significantly colder than at the other temperatures.

4. Discussion

We did not identify any effect of ambient temperature on female endurance performance within the measured temperature range (20 °C to −14 °C). The women's performance, as demonstrated by TTE, did not display any significant differences between the T_a. Nor did we find alterations in the performance-related physiological factors between the T_a, as evidenced by the lack of differences in running economy, running speed at LT and VO_{2max}. Several studies in men have reported that TTE is affected by T_a (Galloway and Maughan, 1997; Parkin et al., 1999; Quirion et al., 1989; Sandsund et al., 2012, 1998). All of these studies, including one performed previously by our group with equivalent clothing, test procedure and T_a (Sandsund et al., 2012), support the idea of a temperature range for optimal performance that can change with the clothing worn, wind and relative humidity. While there is support for a narrow temperature range for optimal male endurance performance, our results did not suggest that the same applies to females.

No differences in VO_{2max} between the T_a (20 °C, 10 °C, 1 °C, −4 °C and −9 °C) were measured. This agrees with the findings of Sandsund et al. (2012, 1998) and Flore et al. (1992). Others have reported reduced VO_{2max} in cold conditions (Kruk et al., 1991; Oksa et al., 2004; Quirion et al., 1989). These authors suggest that the reduced VO_{2max} is due to a shorter TTE or that it is an effect of cold on the muscles. The latter is more likely, because other reports mention shorter TTE with no change in VO_{2max} (Patton and Vogel, 1984; Sandsund et al., 2012, 1998). Furthermore, Bergh and Ekblom (1979) found that to achieve VO_{2max}, core temperature and muscle temperature must be higher than 37.5 °C and 38.0 °C respectively. The dependence on an elevated core temperature to achieve VO_{2max} was also demonstrated by Wiggen et al. (2013). We did not measure muscle temperature in our study, but the core temperature was well above 37.5 °C at the start of the incremental test to exhaustion under all the conditions. Combined with the high T_{re}, the low T_{skin} measured in the cold did not affect the subjects' ability to reach VO_{2max}, which suggests adequate muscle temperature in the working muscles. The lack of VO_2 data from the tests at −14 °C leaves us without exact knowledge of the VO_{2max} at this T_a. However, the performance and performance-related physiological factors at −14 °C did not deviate from the factors at higher T_a.

The women felt cold at the lowest T_a, they also reported the RPE as being extremely hard at the end of the incremental test to exhaustion at all T_a, which means that they pushed themselves to exhaustion in every test, even under the warmest and coldest conditions. Only trained endurance athletes were included in our study, and many were cross-country skiers who exercise and compete outdoors in winter, and were therefore accustomed to performing under cold conditions.

No significant differences in blood lactate concentration at LT or running speed at LT were found between the T_a, but we observed a reduction in $[La^-]_{b\ max}$ under colder ambient conditions. One might expect a higher $[La^-]_b$ in the cold, due to greater reliance on anaerobic metabolism. However, reduced blood flow due to vasoconstriction in the cold could lead to delayed lactate removal from the working muscles to the blood, which can result in a further increase in lactate accumulation in the muscle (Blomstrand and Essèn-Gustavsson, 1987). This would lead to a decreased $[La^-]_b$ in the finger capillaries where our measurements were taken, and a delayed rise in $[La^-]_b$ levels might be difficult to detect in a time-standardised protocol such as that used in our study. This might be supported by the reduced HR_{peak} at low ambient temperatures, which indicates that the amount of circulating blood is less in the cold. We did not find any significant negative effects on performance or performance-related physiological factors at the highest or the lowest $[La^-]_{bmax}$. However, delayed lactate removal may have an effect on shorter-term exercise bouts such as sprints, when athletes depend largely on anaerobic metabolism, which can result in large accumulations of lactate. Reduced performance in short-term exercise bouts is therefore likely if lactate removal is delayed in the cold (Wiggen et al., 2013).

No differences in running economy between the various T_a were measured. This is in accordance with the findings of Stevens et al. (1987), who reported no differences in VO_2 between their female subjects exposed to 5 °C and 21 °C, with equal power output. Other studies, using male subjects, have reported reduced running economy at lower than at higher T_a (Claremont et al., 1975; Galloway and Maughan, 1997; Sandsund et al., 2012, 1998). One of these studies was ours on men, which employed identical methods to those of this study (Sandsund et al., 2012), which makes it likely that the discrepancy between genders are not due to methodological differences, but that there are gender differences in the response to T_a.

Cooling of the muscles diminishes muscular performance, where the degree of cooling correlates with the extent of deterioration (Oksa, 2002). Studies have reported a relationship between low skin temperatures and low muscle temperatures (Blomstrand et al., 1984; Oksa et al., 1997). The lower skin temperature in the cold is a result of vasoconstriction, which reduces the temperature gradient between skin and the ambient air. Women allow their skin temperatures to cool to a greater extent than men, which is clear when comparing the T_{skin} of the women in this study to that of the men in our matching study (Sandsund et al., 2012). Significantly lower T_{skin} was measured in the females than the males at −4 °C, −9 °C and −14 °C (Sandsund et al., 2011). For the women a 13 °C difference in T_{skin} (32 °C and 19 °C) was measured between the warmest (20 °C) and the coldest (−14 °C) conditions, whereas the difference was 10 °C (32 °C and 22 °C) for the men (Sandsund et al., 2012). Wind increases the rate of convective heat loss from the skin to the environment. The effect of wind is apparent on the anterior part of the body in our study. The muscles on the anterior thigh are important during running, but we found no adverse effect on running economy in the women. Heat generated by an active muscle, and the increased blood flow due to the activity, influence muscle temperature. Clarke et al. (1958) observed a temperature gradient from the skin to the muscle that was dependent on the size of the muscle and the amount of subcutaneous fat surrounding it. There is likely to be a connection between adipose tissue thickness and muscle temperature under cold conditions. Women generally have a higher percentage of body fat than men (Graham, 1988), and the women in our study had a higher percentage of body fat (24.5 ± 2.6%) than previously reported in similar studies of male subjects; 15 ± 3%, 17.8 ± 4.1% and 11.9 ± 2.3% (Oksa et al., 1997; Sandsund et al., 2012; Sparks et al., 2005 respectively). A thicker layer of adipose tissue provides increased thermal insulation. Women also tend to have greater thickness of adipose tissue on their arms and legs compared with the trunk than do men (McArdle et al., 1984). The thicker layer of adipose tissue may be the reason why women can reduce their skin temperature while still maintaining a high temperature in the working muscles. It is therefore likely that the thicker layer of adipose tissue provided sufficient protection against heat loss from the working muscles to avoid impairment of performance in our study.

No significant differences in HR were found during the submaximal tests. This is in contrast to several other studies that have reported higher HR under warm than under cool and cold conditions in men (Claremont et al., 1975; Galloway and Maughan, 1997; Kruk et al., 1991; Sandsund et al., 2012). Higher HR under warm conditions can be explained by a reduction in the central blood volume due to redistribution of the blood to the periphery. This may reduce the stroke volume, which in turn may be compensated for to some extent by an increase in HR (Gonzalez-Alonso et al., 1997), also known as cardiac drift (Coyle and Gonzalez-Alonso, 2001). At VO_{2max} we found that HR_{peak} increased with increasing T_a. This rise in HR_{peak} is likely to have been sufficient to compensate for any reduction in stroke volume, since we did not observe any effects on VO_{2max}.

Stevens et al. (1987) studied men and women's cardiovascular responses to cold during rest and exercise. The men responded to moderately warm ambient conditions (21 °C) with a reduction in stroke volume and an increase in HR compared to colder conditions (5 °C). The women showed no differences in response to the two conditions in either stroke volume or HR. An explanation of these gender differences in response to cold exposure was not found, but they were not due to differences in skin temperature, venous noradrenaline levels or body fat. Unlike in the females, the male athletes (Sandsund et al., 2012) displayed a higher HR in moderately warm (20 °C and 10 °C) than in cooler environments (1 °C and −4 °C), as well as impaired performance in moderately warm than in cooler environments. The difference in HR and performance in moderately warm conditions between the men and the women in our studies may be due to the higher loss of body mass at 20 °C in men (1.8%) than in women (1.1%). A study by Grucza (1990) showed that the sweat efficiency, the ratio between secreted and evaporated sweat, is larger in women than men, and thus women lose less of their body mass even when there are no differences in the increases in T_{re} and T_{skin} between the genders. Montain and Coyle (1992) found that HR rises in proportion to the amount of hypohydration experienced during exercise, and found a difference in HR when the subjects had a body mass loss of 1.1% as against 2.3%. According to Murray (2007), performance is affected when the loss is greater than 2% of total body mass. There is also some evidence that supports the idea of impaired performance even at dehydration levels of less than 2% (Greenleaf, 1992; Walsh et al., 1994). Differences in the thermoregulatory response, and therefore the state of hypohydration, might be the reason for the observed difference in HR and performance between males and females under moderately warm conditions.

Comparison of our previous study on men (Sandsund et al., 2012) with this study performed on women makes it clear that the effect of T_a on performance differ between the genders. Where we found no effect of T_a on female performance, male performance was found to be optimal at -1 °C and -4 °C, and performance was reduced under moderately warm and cold ambient conditions. The difference in performance in the cold may be due to a higher heat loss in men. This is supported by the higher T_{skin} in the cold in men than in women, combined with the lower T_{re} seen at -14 °C in men. The difference in performance under moderately warm conditions between the genders may be due to higher sweat efficiency in women, resulting in a lower relative reduction in body mass than in men without any differences in T_{skin} between the genders. These two matching studies support the notion that there are fundamental differences in response to T_a between the genders, and that these differences may affect performance.

5. Conclusions

Female endurance performance, measured as TTE, during one hour of incremental exercise was not affected by T_a that ranged from 20 °C to -14 °C with 5 m s^{-1} winds.

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References

(ISO), I.O.f.S., 2005. Ergonomics of the thermal environment—Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and local Thermal Comfort Criteria (Standard No. ISO 7730:2005). Geneva, Switzerland.

Bell, M.P., Ferguson, R.A., 2009. Interaction between muscle temperature and contraction velocity affects mechanical efficiency during moderate-intensity cycling exercise in young and older women. J. Appl. Physiol. 107, 763–769.

Bergh, U., Ekblom, B., 1979. Physical performance and peak aerobic power at different body temperatures. J. Appl. Physiol. 46, 885–889.

Blomstrand, E., Bergh, U., Essèn-Gustavsson, B., Ekblom, B., 1984. Influence of low muscle temperature on muscle metabolism during intense dynamic exercise. Acta Physiol. Scand. 120, 229–236.

Blomstrand, E., Essèn-Gustavsson, B., 1987. Influence of reduced muscle temperature on metabolism in type I and type II human muscle fibres during intensive exercise. Acta Physiol. Scand. 131, 569–574.

Borg, G., 1970. Perceived exertion as an indicator of somatic stress. Scand. J. Rehabi. Med. 2, 92–98.

Claremont, A., Nagle, F., Reddan, W., Brooks, G., 1975. Comparison of metabolic, temperature, heart rate and ventilatory responses to exercise at extreme ambient temperatures (0 °C and 35 °C). Med. Sci. Sports 7, 150–154.

Clarke, R., Hellon, R., Lind, A., 1958. The duration of sustained contractions of the human forearm at different muscle temperatures. J. Physiol. 143, 454–473.

Coyle, E., Gonzalez-Alonso, J., 2001. Cardiovascular drift during prolonged exercise: new perspectives. Exerc. Sport Sci. Rev. 29, 88–92.

Ferretti, G., Ishii, M., Moia, C., Cerretelli, P., 1992. Effects of temperature on the maximal instantaneous muscle power of humans. Eur. J. Appl. Physiol. Occup. Physiol. 64, 112–116.

Flore, P., Therminarias, A., Oddou-Chirpaz, M., Quirion, A., 1992. Influence of moderate cold exposure on blood lactate during incremental exercise. Eur. J. Appl. Physiol. Occup. Physiol. 64, 213–217.

Galloway, S.D.R., Maughan, R.J., 1997. Effects of ambient temperature on the capacity to perform prolonged cycle exercise in man. Med. Sci. Sports Exerc. 29, 1240–1249.

Gonzalez-Alonso, J., Mora-Rodriguez, R., Below, P.R., Coyle, E.F., 1997. Dehydration markedly impairs cardiovascular function in hyperthermic endurance of athletes during exercise. J. Appl. Physiol. 82, 1229–1236.

Graham, T., 1988. Thermal, metabolic, and cardiovascular changes in men and women during cold stress. Med. Sci. Sports Exerc. 20, 185–192.

Greenleaf, J.E., 1992. Problem: thirst, drinking behavior, and involuntary dehydration. Med. Sci. Sports Exerc. 24, 645–656.

Grucza, R., 1990. Efficiency of thermoregulatory system in man under endogenous and exogenous heat loads. Acta Physiol. Pol. 41, 123.

Helgerud, J., Ingjer, F., Strømme, S., 1990. Sex differences in performance-matched marathon runners. Eur. J. Appl. Physiol. Occup. Physiol. 61, 433–439.

Kaciuba-Uscilko, H., Grucza, R., 2001. Gender differences in thermoregulation. Curr. Opin. Clin. Nutr. Metab. Care 4, 533–536.

Kruk, B., Pekkarinen, H., Manninen, K., Hänninen, O., 1991. Comparison in men of physiological responses to exercise of increasing intensity at low and moderate ambient temperatures. Eur. J. Appl. Physiol. Occup. Physiol. 62, 353–357.

McArdle, W., Magel, J., Spina, R., Gergley, T., Toner, M., 1984. Thermal adjustment to cold-water exposure in exercising men and women. J. Appl. Physiol. 56, 1572–1577.

Montain, S.J., Coyle, E.F., 1992. Influence of graded dehydration on hyperthermia and cardiovascular drift during exercise. J. Appl. Physiol. 73, 1340–1350.

Murray, B., 2007. Hydration and physical performance. J. Am. Coll. Nutr. 26, 542–548.

Oksa, J., 2002. Neuromuscular performance limitations in cold. Int. J. Circumpolar Health, 61.

Oksa, J., Kaikkonen, H., Sorvisto, P., Vaappo, M., Martikkala, V., Rintamaki, H., 2004. Changes in maximal cardiorespiratory capacity and submaximal strain while exercising in cold. J. Therm. Biol. 29, 815–818.

Oksa, J., Rintamaki, H., Rissanen, S., 1997. Muscle performance and electromyogram activity of the lower leg muscles with different levels of cold exposure. Eur. J. Appl. Physiol. Occup. Physiol. 75, 484–490.

Olesen, S., Fanger, P.O., Bassing, J.J., 1972. Physiological comfort conditions at sixteen combinations of activity, clothing, air velocity and ambient temperature. ASHRAE Trans. 78, 199–203.

Parkin, J., Carey, M., Zhao, S., Febbraio, M., 1999. Effect of ambient temperature on human skeletal muscle metabolism during fatiguing submaximal exercise. J. Appl. Physiol. 86, 902–908.

Patton, J.F., Vogel, J.A., 1984. Effects of acute cold exposure on submaximal endurance performance. Med. Sci. Sports Exerc. 16, 494–497.

Quirion, A., Laurencelle, L., Paulin, L., Therminarias, A., Brisson, G., Audet, A., Dulac, S., Vogelaere, P., 1989. Metabolic and hormonal responses during exercise at 20 °C, 0 °C and -20 °C. Int. J. Biometeorol. 33, 227–232.

Racinais, S., Oksa, J., 2010. Temperature and neuromuscular function. Scand. J. Med. Sci. Sports 20, 1–18.

Rowland, T., Hagenbuch, S., POBER, D., Garrison, A., 2008. Exercise tolerance and thermoregulatory responses during cycling in boys and men. Med. Sci. Sports Exerc. 40, 282–287.

Sandsund, M., Renberg, J., Saursaunet, V., Wiggen, Ø., Færevik, H., Tjønnås, M., Reinertsen, R., 2011. Gender differences and thermoregulatory responses during exercise in warm and cold environments. In: Kounalakis Stylianos, K. M. (Ed.), The 14th International Conference on Environmental Ergonomics. Greece.

Sandsund, M., Saursaunet, V., Wiggen, Ø., Renberg, J., Færevik, H., van Beekvelt, M. C., 2012. Effect of ambient temperature on endurance performance while wearing cross-country skiing clothing. Eur. J. Appl. Physiol. 112, 3939–3947.

Sandsund, M., Sue-Chu, M., Helgerud, J., Reinertsen, R.E., Bjermer, L., 1998. Effect of cold exposure (-15 °C) and Salbutamol treatment on physical performance in elite nonasthmatic cross-country skiers. Eur. J. Appl. Physiol. Occup. Physiol. 77, 297–304.

Sparks, S., Cable, N., Doran, D., Maclaren, D., 2005. The influence of environmental temperature on duathlon performance. Ergonomics 48, 1558–1567.

Stephenson, L.A., Kolka, M.A., 1993. Thermoregulation in women. Exerc. Sport Sci. Rev. 21, 231–262.

Stevens, G.H.J., Graham, T., Wilson, B., 1987. Gender differences in cardiovascular and metabolic responses to cold and exercise. Can. J. Physiol. Pharmacol. 65, 165–171.

Stocks, J.M., Taylor, N.A.S., Tipton, M.J., Greenleaf, J.E., 2004. Human physiological responses to cold exposure. Aviat. Space Environ. Med. 75, 444–457.

Walsh, C., Graham, T., 1986. Male-female responses in various body temperatures during and following exercise in cold air. Aviat. Space Environ. Med. 57, 966–973.

Walsh, R., Noakes, T., Hawley, J., Dennis, S., 1994. Impaired high-intensity cycling performance time at low levels of dehydration. Int. J. Sports Med. 15, 392–398.

Wiggen, Ø.N., Waagaard, S.H., Heidelberg, C.T., Oksa, J., 2013. Effect of cold conditions on double poling sprint performance of well-trained male cross-country skiers. J. Strength Cond. Res./Natl. Strength Cond. Assoc. 27 (12), 3377–3383.