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The effect of low temperatures on muscle function while wearing protective clothing used in the mining industry

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Preface

I want to give my thanks to SINTEF Technology and Society, dep. of Health Research for giving me the opportunity to write my master thesis under their guidance and supervision. Especially thanks to project manager at SINTEF, dr. Hilde Færevik for inviting me into this project. Also thanks to dr. Øystein Wiggen; you have been a humble and educating tutor, and given me the feeling of both being an independent student as well as being a part of your team at SINTEF. I would also like to thank main supervisor ass. Prof. Mireille Christine Petrine Van Beekvelt and prof. Karin Roeleveld, NTNU, for much appreciated follow-up and excellent feedback during this process.

This master's thesis has been conducted at the Human Movement Science programme at the Norwegian University of Science and Technology (NTNU), and is part of the MineHealth project (http://minehealth.eu/), which SINTEF is attending as one of the partners.

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ABBREVATIONS

BPM – Beats per minute

DWF – Dynamic wrist flexion

ED – Extensor digitorum

EMG – Electromyography

FDS – Flexor digitorum superficialis

HHb – Deoxyhaemoglobin

HR – Heart rate

MVC – Maximal voluntary contraction

NIRS – Near-infrared spectroscopy

O_2Hb – Oxyhaemoglobin

PTS – Perceived thermal sensation

PTC – Perceived thermal comfort

RPE – Rate of perceived exertion

SD – Standard deviation

tHb – Total haemoglobin

ABSTRACT

The purpose of this study was to investigate how muscle function is affected by cold environments in persons wearing cold protective clothing for the mining industry when performing work-related tasks. 15 subjects were exposed to a low temperature (-15°C) and a moderate temperature (5°C). Protective clothing was similar during both environmental conditions. The subjects performed a total of five test periods and four work periods. A test period consisted of dynamic wrist flexion and maximal voluntary contractions for wrist flexion, elbow flexion and shoulder abduction. Work periods consisted of three tasks; 1) arms above head, 2) arms at hip height and 3) lifting dumbbells of the floor and onto a case. Cold exposure led to lower skin temperatures and higher muscle activity in the wrist flexors during the work period compared to 5°C. In addition, we observed a reduced amount of local oxygenation in the wrist flexors in the cold. In conclusion, cold exposure reduced skin temperatures, which further led to minor negative effect on muscle function.

INTRODUCTION

The Barents region has many natural resources that promote growth and employment in the petroleum- and mining industry. New mines are opening in several locations, and old mines are expanded or reopened. Working as a miner is still associated with risk for reduced health with individual suffering and increased costs for the enterprises and society (http://minehealth.eu/about/). The MineHealth project has been established with an overall objective to provide long-term sustainability of well-being, health and work ability among workers in the mining industry (http://minehealth.eu/).

This is achieved by increased and updated knowledge on how to cope with the environment and to adopt preventive measures for working in the mining industry within the Barents region. This part of MineHealth is looking at the effects of cold exposure in a realistic work setting. It is common with low ambient temperatures combined with wind when working outside in the Northern regions. Muscle cooling leads to an increased muscle activation, earlier fatigue and in general a reduced muscle function (Oksa et al. 2002). There are also great variations considering work tasks in the mining industry. It may vary from stationary fine motor work to demanding whole-body work. Different tasks leads to large variations in body position such as standing, sitting and working prone. Various body positions leads to different loads, where unfavourable positions can cause discomfort and earlier fatigue.

Human thermoregulation

Human beings continuously strive to maintain body heat balance via several thermoregulatory mechanisms. These mechanisms maintain homeostasis: ensuring that the human body has a relative constant temperature (37°C), and rarely deviates from this (Blaxter 1989). The main factors that affect human thermal balance are the environment (ambient temperature, radiant temperature, wind and humidity), metabolic heat production (duration, intensity and type) and clothing (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 warm and cold environments, and body size. The effective ambient temperature a human body is exposed to during activity, depends not only on the ambient temperature, but also on wind chill temperature, and the velocity of the movement (McArdle et al. 2007). Thermoregulation in general is achieved by several adjustments in heat gain and heat loss mechanisms.

Skin temperature varies on different places of the body; parts that are more distal are cooler than central places on the body. Oksa et al. (2002) demonstrated that when the forearm skin temperature was reduced systemic from 34ºC to 29ºC, this resulted in a lower endurance, force and power performance of the working muscle. Increased muscle activation and a decreased maximal voluntary contraction (MVC) was one of the seen effects of muscle cooling. A reduced muscle temperature may also change the muscle fiber recruitment from type 1 to type 2 (Rome et al. 1984). Blomstrand et al. (1984) suggested that higher levels of lactate are reached with low muscle temperatures. Clarke et al. (1958) found that when the forearm temperature was decreased in a water bath, from 35ºC to 25ºC, blood flow and duration of sustained contractions was significantly reduced. Furthermore, lower tissue temperature has been shown to increase resistance in the finger joints and reduced mobility (Hunter et al. 1952).

If body temperature decrease, blood is redistributed from the periphery to the core for heat preservation. Peripheral blood vessels constrict and creates an additional increase in vascular resistance. However, if body temperature increase, the opposite effect is seen. The blood vessels dilate, and blood flow increases due to a decrease in vascular resistance (Guyton et al. 2006). Warm blood is transported to the peripheries, and if the environment is colder than the skin, the warmth from the blood will lead to heat loss through the skin through conduction, convection, radiation and evaporation of sweat (Gisolfi & Wenger 1984).

Muscle function

The majority of studies that investigated the effect of temperature on muscle function have primarily made use of electromyography (EMG) as an expression of muscle function. Muscles are activated through electrical signals that can be recorded in the muscle (needle/wire EMG), or on the skin above the muscle (surface EMG). The signal amplitude gives insight in the number of active motor units and their firing rate, while the frequency content of the signal mainly reflects action potential shape (Konrad 2006). Muscle force production is initiated by the generation of action potentials by a number of active motor units. This results in a traveling electrical action potential that culminates with muscle activation and force production (Konrad 2006). Dynamic force production is highly temperature dependent, and even a slightly lower muscle temperature can influence the co-contraction of the agonist-antagonist muscle pairs, and result in a “braking effect” and reduced muscle power (Oksa et al. 2002). When muscle temperature is reduced, it is possible

to identify changes in EMG activity at a given workload, e.g. indicating the amount of fatigue in a muscle. Increased EMG amplitude at the same submaximal workload indicates that the already active motor units is becoming tired and less efficient. Thus, the need for more active motor units are necessary. This is one of the mechanisms behind muscle cooling (Blomstrand et al. 1984). In addition, muscle cooling can lead to a reduced conduction velocity through alterations in the firing frequency of the motor units (Oksa et al. 1997, Mucke et al. 1989). The following changes and differences in the EMG signal can signify muscle fatigue: an increase in the mean absolute value of the signal, increase in the amplitude and duration of the muscle action potential and an overall shift to lower frequencies, which in turn may result in a slower and weaker muscle contraction (Denys 1991). It has also been shown that when muscle temperature decreases, muscle activity of the agonists are decreased, while that the activity of the antagonists increases (Berg & Ekblom 1979). EMG have been used in several previous studies on cold environments, and is used as a measurement tool in our study to investigate to which extent cold affects muscle activity.

Near-infrared spectroscopy (NIRS) is a non-invasive, continuous and direct method to determine oxygenation and haemodynamic in tissue. Normal microcirculation is a requirement for normal muscle function. Lowered muscle temperature affects microcirculation in the tissue, and is thus a threat for normal muscle function (Clarke et al. 1958). By utilizing NIRS, it is possible to investigate what happens inside the tissue during cold exposure. Previous studies using NIRS have shown to be a sensitive tool in the discrimination between normal and pathological states (Van Beekvelt et al. 2001). To the best of our knowledge, there is limited studies on how low temperatures affects the tissue measured with NIRS. In this study, NIRS may provide us with useful information regarding how the muscles local oxygenation changes in cold (-15 °C) vs. warmer (5°C) environments. If muscle function reduces in cold environments, EMG and NIRS in combination might provide a better and more nuanced picture of the mechanisms that lies behind a decreased muscle function than previous studies.

What is new in this study is that the subjects was dressed with cold protective clothing, exposed to realistic temperatures and set to perform realistic work-related tasks for mineworkers. In addition, we used NIRS measurements. Regarding how low ambient temperature affects muscle function when wearing cold protective clothing are the essential part in this study. The aim was to investigate if exposure to -15 °C combined with realistic

work tasks and cold protective clothing, will negatively affect muscle function evaluated by EMG, force and NIRS, compared to a 5°C exposure.

It was hypothesized that cold conditions (-15°C) will cause detrimental effects on muscle function when performing realistic work tasks while wearing cold protective clothing. We expect that cold exposure will lead to:

a) Thermal responses. Reduced skin temperatures when exposed to -15°C compared to 5°
b) Reduced muscle oxygenation in -15°C compared to 5°C (NIRS)
c) No difference in isometric strength (force).
d) A higher activation in muscle activity in -15°C compared to 5°C.

METHODS AND MATERIALS

Subjects

Fifteen trained male subjects participated in this randomized study. All subjects voluntarily participated in this study and signed a consent form to verify this. The inclusion criteria were age between 20-40 years, normal BMI (18.5-24.9 kg/m^2) or a body fat percent < 20%, height between 175-200 cm and an approved medical examination. The exclusion criteria were all kinds of cold injuries or white fingers (Raynaud's syndrome) and illnesses. Termination criteria's during the experimental protocol were; rectal temperature (T_{re}) below 35°C or a decrease with more than 2°C from baseline value, skin temperature continuously below 10°C for more than 20 minute or absolute below 8°C. The subjects could terminate the test at any time. The regional committee for medical and health research ethics (REK North) approved the study. The physical characteristics of the subjects are shown in Table 1. Adipose tissue thickness was sampled to estimate the penetration depth of NIRS.

Table 1. Physical characteristics of participants. Data are means ± SD. N=15.

Age (years)	Body mass (kg)	Body fat (%)	Height (cm)	BMI	Adipose tissue thickness
25 ±3.1	80.8 ±6.1	14.9 ±1.7	182 ±5.3	24.14 ±1.3	3.2 ±1.3

Experimental protocol

A schematic representation of the experimental protocol is shown in Figure 1. The protocol consisted of two trials: one trial in -15°C and one trial in 5°C (control). Both protocols were identical, except for the ambient temperature.

First, the subject went through a preparation phase of about 60 minutes where all sensors were placed and the subjects instructed. The subjects put on the standardized set of clothing before each test started with a 20 minutes pre-test rest period. The subject then sat in a room at approximately 23°C in order to stabilise body temperature and heart rate before entering the climatic chamber. This chamber was regulated to hold either 5°C or -15°C. After preparation, the subjects entered the climate chamber and completed the protocol inside. A detailed representation of the protocol is shown in Figure 2. The protocol consisted of five test periods

(of 12 minutes duration), and four work periods (of 15 minutes duration). Test periods consisted of four different tasks sitting down. Work periods consisted of three different tasks standing. The protocol lasted for a total of 120 minutes.

Each participant visited the lab on three separate days. One preliminary session, which consisted of descriptive measurements, as well as getting the subjects familiarized with the experimental protocol and equipment. In addition, a 10 minutes NIRS occlusion test was done to determine max desaturation levels. This data was obtained by occluding the upper arm for 10 minutes, while continuously NIRS measurements were done at the left flexor digitorum superficialis (FDS). Then the subjects visited the lab for one cold session and one warmer session (-15°C and 5°C). The order of these sessions were counterbalanced in a randomized order. Seven subjects attended the cold session as the first trial, and eight subjects attended the warmer session as the first trial.

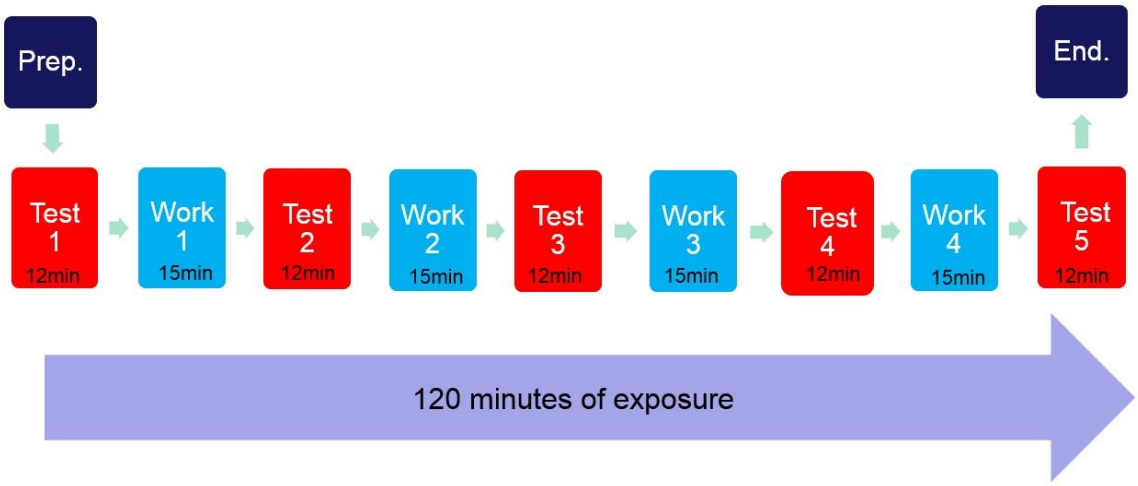

Fig. 1. Schematic representation of the protocol. NIRS + EMG was measured continuously. Analysis was done on part of the data. See METHODS for detailed description of the protocol.

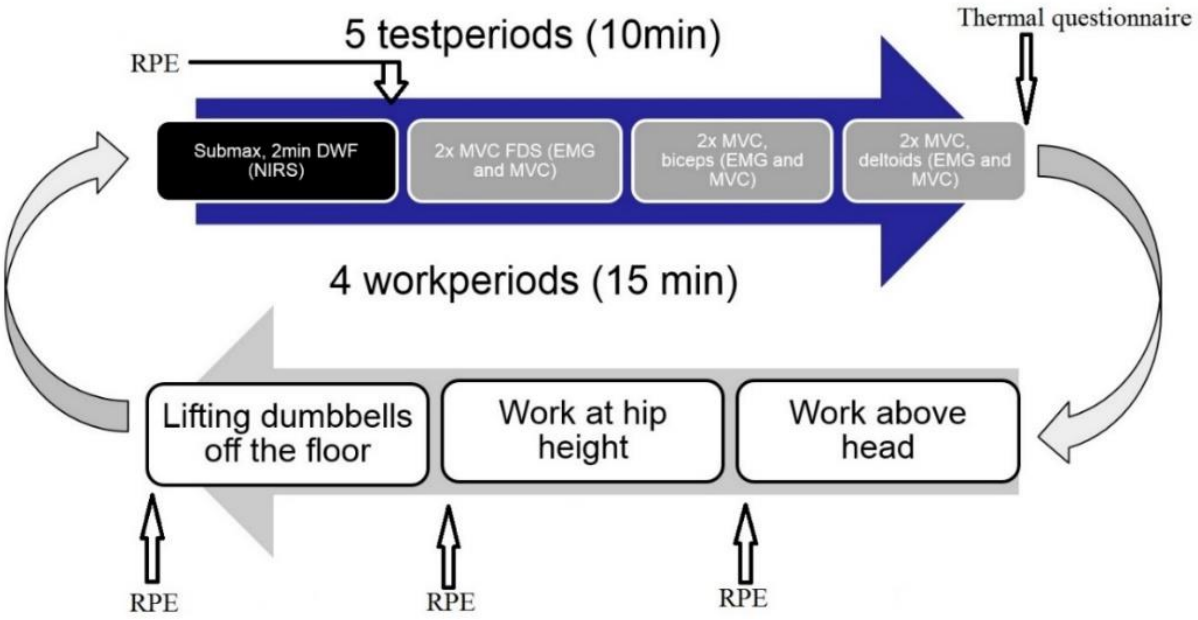

Fig. 2. Detailed schematic overview of the protocol, test and work periods. The protocol started and ended with a test period. Test 1: Dynamic wrist flexion (DWF) for 2 minutes. Test 2: 2x MVC wrist flexion. Test 3: 2x MVC elbow flexion. Test 4: 2x MVC shoulder abduction. A rating of perceived exertion (RPE) was obtained after each dynamic wrist flexion (DWF) and following each work task. RPE of work periods are not included in the report. Thermal sensation and comfort was obtained when finishing a test period.

Test periods

Dynamic wrist flexion (DWF) was the first test in each of the five test periods and started one minute after the subject entered the climate chamber, with two minutes of DWF performed with the left arm (figure 3). The subjects lifted a 0.5 kg dumbbell, 40 lifts per minute by following a metronome from the climate chamber's speaker system. During the test periods, the subjects were sitting in a customized built chair, with both arms resting on an armrest, their forearms supinated and with a 90° elbow angle (figure 3).

Following the DWF test, a set of standardized MVC tests was performed. Each contraction had a duration of two-three seconds and was performed twice with a two second break in between. The contraction with the highest EMG amplitude was used for further analyses. This amplitude can be used to normalize the EMG amplitude so that it may be expressed as percentage of maximal activation. MVC was performed with a right and left wrist flexion and extension (figure 3). Further, right elbow flexion, elbow extension, shoulder abduction and shoulder extension. Data from these muscles are however not presented in this report.

During test period two, three, four and five, only wrist flexion, elbow flexion and shoulder abduction MVC was collected after each DWF. When subject performed the isometric contraction by wrist flexors and elbow flexors, a force cell registered the amount of force produced during these tests. Arm was resting on an armrest with an elbow angle of 90° and wrist in a supinated position (figure 3). Shoulder abduction MVC was the last test in the test period. Subjects were instructed to lift two handles bilaterally that were attached to the ground. Shoulder angle was approximately 80°. Then on command, pull arms upwards for two-three seconds. A force cell attached to the right side, registered to the amount of force produced from this test. The subjects then moved on to the work period. Force data from this test is not presented in this report.

Fig. 3. Right wrist flexion MVC. Arm resting on an armrest, elbow angle in approximately 90° and forearm supinated. The same position was also applied for DWF.

Work periods

Each work period consisted of three tasks: the first was manual work with arms above head. In detail, the subject were to hang every third chain joint on a hook, then tie four knots in a climbing rope and then work with the chain (figure 4). After a one-minute brake, the second task was performed, which was identical to the previous task, only with arms in hip height for five minutes, then another minute brake. The third task consisted of lifting a set of five kg dumbbells off the floor and onto a 0.5m high case and down again. This test was supposed to illustrate work below hip height. Each of the tasks were performed continuously for five minutes. After the third task, the subjects moved on to the next test period. The subjects completed a total of five test periods and four work periods. The protocol started by taking place in the chair where the subjects did the tasks in test period, and ended with a fifth test period.

Experimental protocol pictures

Figure 4 illustrates tasks from the protocol.

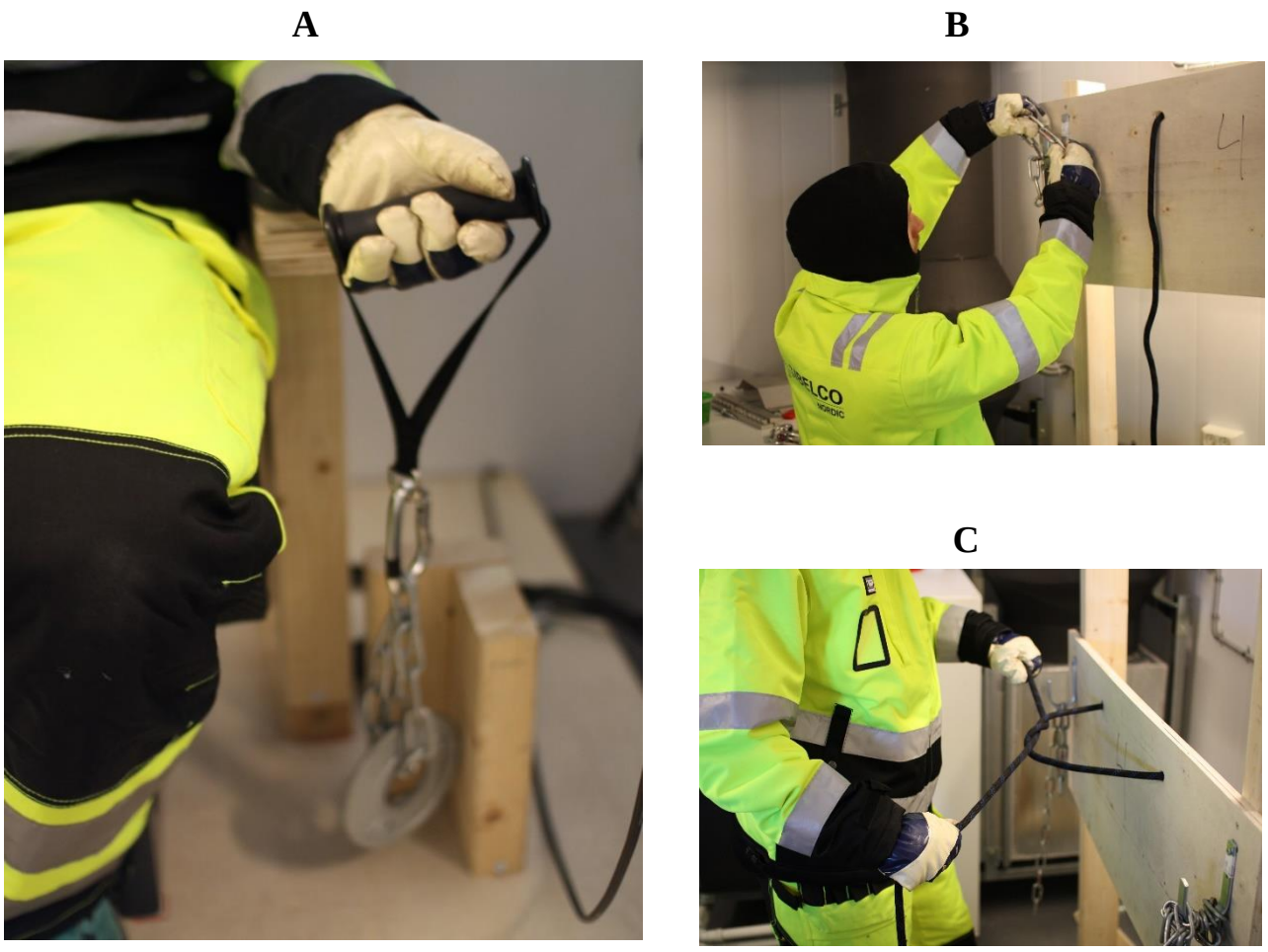

Fig. 4. Illustration from the protocol. A) dynamic wrist flexion. Subject sitting in the customized built chair. Arm is resting with elbow in a 90°, wrist in a supinated position. B) Subject is doing manual work above head. Hanging chains on a hook, tying four knots in a rope and working with the chains again. This task were done continuously for five minutes. Subjects were instructed to keep arms above head at all times during this task. C) Same work as above head, but at hip height for five minutes.

Equipment and measurements

Temperature

Skin temperature was measured by placing skin thermistors (YSI 400, Yellow Springs Instrument Co., Yellow Springs, Ohio, USA) on 12 various locations on the body: Forehead, right chest, scapulae, stomach, upper arm, lower arm, hand, long finger, anterior/posterior thigh and anterior/posterior calf. The skin was, if necessarily, dry shaved to get proper adherence and measurements. These thermistors were attached to the body with adhesive tape. A commonly used way to express the overall skin temperature is the weighted mean skin temperature (MST): MST was calculated as: 0.149*T forehead, 0.186* T chest, 0.186*T back, 0.107*T upper arm, 0.186*T anterior thigh, 0.186*T posterior thigh (Teichner, 1958). A rectal probe (YSI 700, Yellow Springs Instrument Co., Yellow Springs, Ohio, USA) was used to detect core temperature.

Heart rate

A heart-rate monitor (Polar S810TM Electro OY, Kempele, Finland, accuracy ± 2 beats·min-1) was used to continuously measure HR during the test.

Subjective measurements of exertion and thermal sensation

RPE using Borg scale, was obtained after each DWF, and following each work task. When finishing a test period, the subjects had to give an indication of perceived thermal sensation on whole body, hands, feet and head. They also had to report a level of shivering/sweating, and how the ambient temperature felt thermally on a standardized scale (see appendix 1 – Subjective thermal sensation for details).

NIRS

In order to obtain information about local difference in muscle oxygenation and saturation, we used near-infrared spectroscopy (NIRS). NIRS is based on the relative tissue transparency for light in the near-infrared region and on the oxygen-dependant absorption changes of haemoglobin and myoglobin (Van Beekvelt et al. 2001). In this study, we looked at changes in deoxygenation rates during exercise that was repeated over a two hour exposure to cold and whether these deoxygenation changes were different for -15°C in comparison with 5°C. The sum of oxyhaemoglobin (O_2Hb) and deoxyhaemoglobin (HHb) concentrations in the

measured muscle reflects the total amount of total haemoglobin (tHb) (Van Beekvelt et al. 2001). It is also possible to measure muscle oxygen saturation (SmO_2) as a product of the mentioned variables. The distance between the three light transmitters and the detector for the NIRS (Portamon, Artinis Medical Systems, Netherlands) probe was 35mm, enabling a maximum penetration depth up to 17.5mm. Continuously NIRS measurements were made on top of the left FDS muscle along with the muscle fibres. An elastic band and adhesive tape was attached over the probe to secure that the probe stayed in the same place during the whole test. The probe was positioned at the exact same place for both tests by marking the skin after the first test. Data was sampled at 10Hz, displayed real-time and stored on disk for analysis

Force

Muscle force during right isometric wrist flexion and elbow flexion was measured using a force cell (Noraxon DTS Force Sensor, Noraxon Inc., Scottsdale, Arizona, U.S). Data was collected together with the EMG signals with a sampling rate of 1500Hz. Force measurements from elbow flexion is not included in this report.

EMG

To measure muscle activity, we used surface EMG electrodes with an inter-electrode distance of one cm (Noraxon DTS Surface EMG, Noraxon Inc., Scottsdale, Arizona, U.S). For each site, a dual self-adhesive, disposable, pre-gelled surface Ag/AgCl electrode was attached to the skin in line with the muscle fibers (Noraxon dual electrodes Ag/AgCl, Noraxon Inc., Scottsdale, Arizona, U.S). Prior to electrode attachment, the skin was shaved when necessary, rubbed with a special abrasive lotion and cleansed with an ether/alcohol mixture in order to secure optimal electrode-adherence. The electrodes were positioned at the same place during both tests by marking the skin after the first test. EMG signals were amplified (500x), band pass filtered (20-500Hz), displayed real-time and digitized with a sampling rate of 1500Hz. EMG data from right FDS and extensor digitorum (ED) are presented in this report.

Clothing

All subjects wore a standardized set of clothing consisting two layers. Inner layer consisted of wool socks, wool pants, wool sweater and a boxer of choice. Outer layer consisted of insulated jacket, pants and industry work shoes. The subjects also wore a wool balaclava and

wool mittens. Clothing insulation can be expressed in Clo units. 1 Clo = 0.155 K·m²/W. Thermal insulation for the whole clothing ensemble was 2.7 Clo. Subjects were instructed to keep gloves and balaclava on, but could if necessary open the zipper on the jacket if feeling to warm.

Data analysis

Heart rate and temperature

HR and skin temperature were sampled in Excel (Microsoft Inc., Redmond, Washington, U.S) as the mean value over every five minutes for all subjects and both temperatures. Mean (± SD) was calculated in SPSS 18.0 (SPSS Inc., Chicago, IL, USA)

NIRS

The NIRS signals during the dynamic wrist flexion task of each of the five test periods was used for further analysis. Group responses for changes in oxyhaemoglobin (O_2Hb), deoxyhaemoglobin (HHb) and total haemoglobin (tHb) are calculated after normalization and presented as one sample. For concentrations values, delta values were calculated as the difference between baseline and end-exercise. Baseline concentrations were determined as the mean over the last 30 seconds prior to exercise. End-exercise concentrations were determined as the mean over the 30 last seconds of the task. Data was analysed in Matlab (Mathworks Inc., Natick, Massachusetts, U.S). The concentration changes were measured as micromolars (µM). Filtering of the raw NIRS signal was done with an 8^{th} order Butterworth low-pass filter in order to remove the contraction-relaxation artifacts.

Force

Muscle force (N) was analysed with Noraxon's own computer software (MyoResearch XP Noraxon Inc., Scottsdale, Arizona, U.S). Peak force was low pass filtered and defined as peak amplitude.

EMG

Muscle activation was analysed with Noraxon's computer software. Digitized data was high pass filtered (30Hz) to remove movement artifacts. MVC data was analysed based on the root

mean square (RMS) calculation with a sampling window of 50ms. The RMS reflects the mean power of the signal (Konrad, 2006). Work tasks were calculated by RMS with a sampling window of 50ms. Max activation was in this study defined as maximum amplitude from each muscles MVC test. These MVC values were set as the 100% capacity for both muscles. Mean amplitude from each work task was collected individually, and calculated to a percent value from the muscles actual MVC value (100 • mean amplitude from task/max amplitude from MVC). This makes it possible to identify the percentage use of max capacity from each particular task (figure 5). EMG data is presented in amplitude (µV) and amplitude (percentage of max activation). When presenting data as un-normalized values as primarily done in this report, one is not dependent of a correct performed MVC done prior to the trial. EMG values from manual work above head and at hip height are presented in this paper.

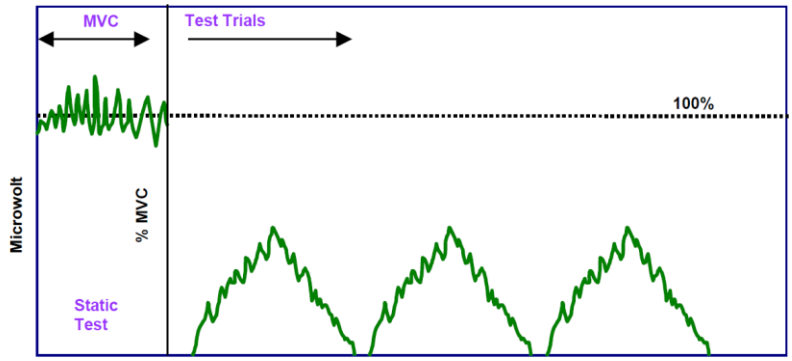

Fig. 5. The concept of MVC normalization. Prior to the each, an isometric contraction was performed for each muscle. This MVC innervation level serves as reference level (=100%) for all forthcoming trials (Konrad. The ABC of EMG).

Statistical design

Statistical analyses were performed in SPSS 18. Two-way ANOVA repeated measurements was used to determine changes between ambient temperature and time (minutes exposed) for temperature, HR, and NIRS data. A general linear model repeated measurement was used for the EMG data. Non-parametric tests were performed on the subjective evaluation scores, where Wilcoxon Signed rank was used. All data in tables and figures are presented as mean and standard deviation (SD). Data were accepted as statistically significant at $p<0.05$, indicated by *.

RESULTS

All 15 subjects attended and completed both trials. However, there was some missing data in temperature, heart rate and EMG data due to equipment failures.

Temperature

In skin temperature in general, there was a significant difference between temperatures of -15°C compared to 5°C.

A significant difference in MST was found between the ambient temperatures of -15°C and 5°C. In -15°C, MST decreased significantly steeper and to a lower temperature during -15 °C than during 5°C (figure 6a).

Similar results as for MST were found for forearm temperature (figure 6b). A significant difference in forearm temperature was found between the two ambient temperatures. At the right forearm in 5°C, 31.8°C was measured as the lowest temperature after 10 minutes of exposure. During -15°C, 30°C was measured as the lowest temperature after 118 minutes of exposure.

Finger temperature showed the largest fluctuations and the lowest temperatures. As for the other skin temperatures, the difference in finger skin temperature between the -15°C and 5°C were significant. The lowest finger temperature measured were 13.2°C after 45 minutes and 27.2 after 30 minutes for -15°C and 5°C respectively. Several subjects were struggling with the tasks due to cold fingers. Some subjects were close to being excluded because of too low finger temperatures (figure 6c).

Core temperature (T_{re}) showed no significant differences between the ambient temperatures (figure 6d).

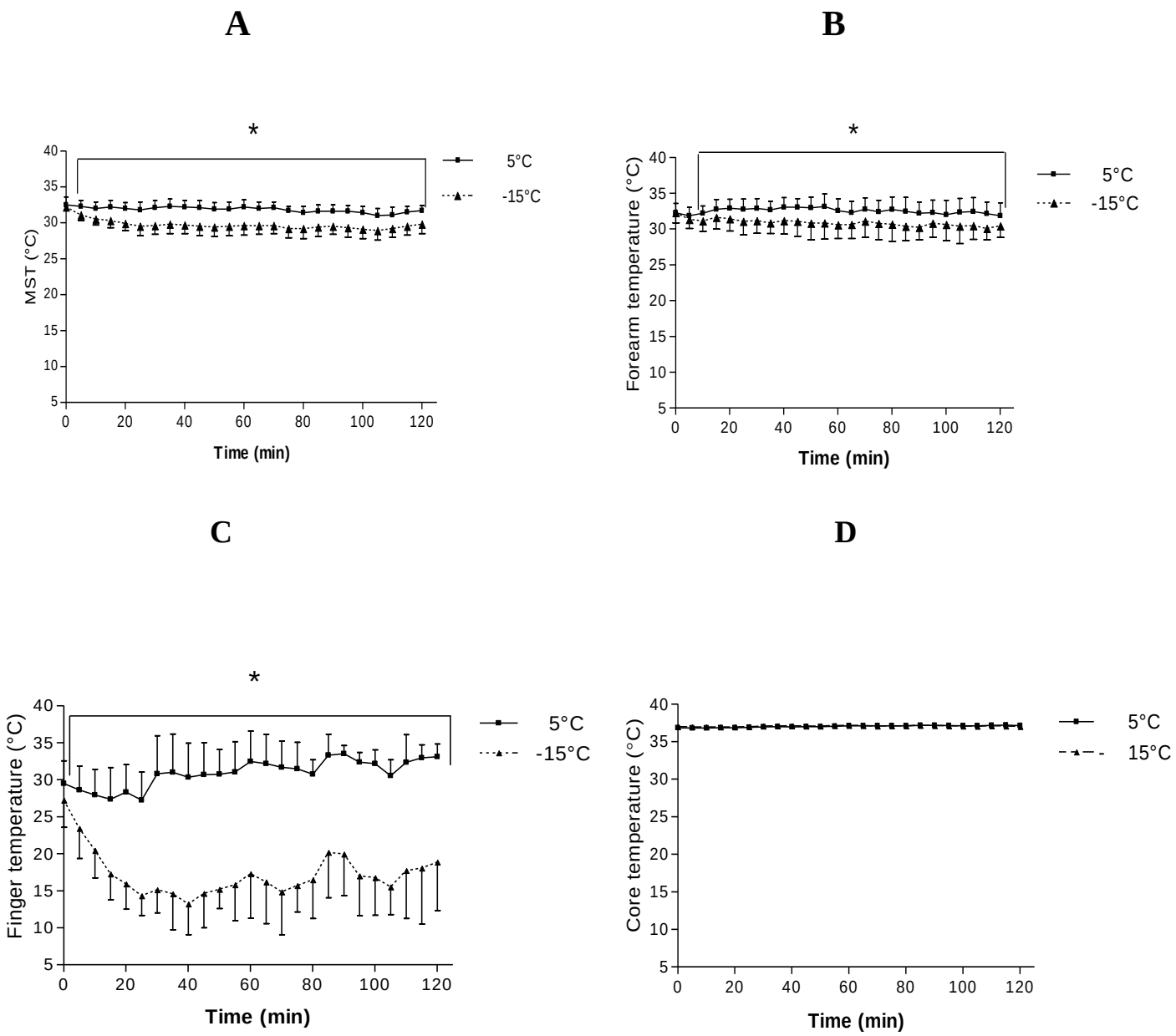

Fig. 6. MST (A), forearm temperature (B), finger temperature (C) and core temperature (D) for both ambient temperatures 5°C and -15°C. There was a significant difference between all skin temperatures. Marked values indicates a significant difference between -15°C compared to 5°C. No significant difference was found in core temperature. N=13 for A, B and C. Regarding D, N=eight.

Heart rate

There were no significant differences in HR between 5°C and -15°C (figure 7).

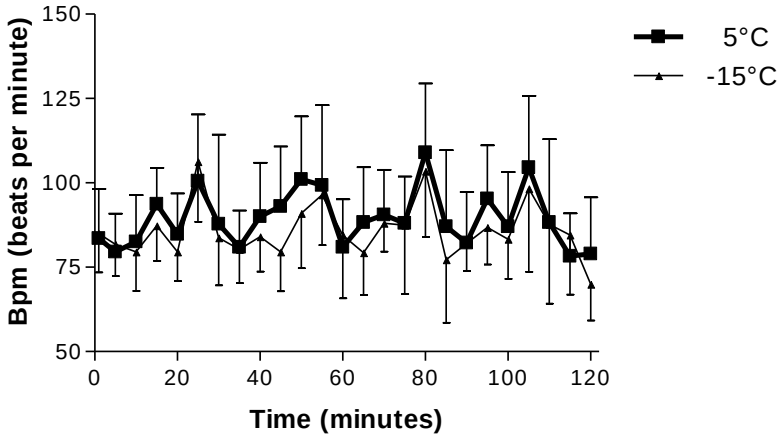

Fig. 7. Heart rate during 5°C and -15°C. Mean (SD ±) are shown each fifth minutes. N=seven. No significant difference in HR was found between the temperatures.

Borg scale and thermal sensation

Rate of perceived exertion (RPE) during dynamic wrist flexion

After the two minutes of DWF, the subjects gave reported RPE (figure 8). When comparing the two first test periods, there is no significant difference in reported strain between the ambient temperatures. However, we found a significant difference when comparing the last three test periods. Subjects reported a higher grade of strain in 5°C than in -15°C.

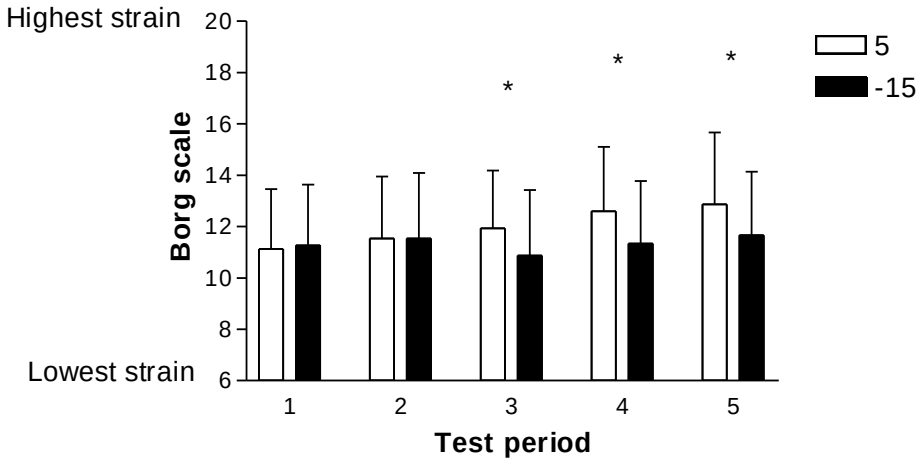

Fig. 8. Perceived exertion using Borg scale, DWF for two minutes. N=15. A significant higher grade of exertion was found in 5°C in the three last test periods compared to -15°C.

Perceived thermal sensation

The perceived thermal sensation showed that the subjects were feeling colder on hands, feet and head in -15°C than in 5°C. Differences between the temperatures were significant. Subjects reported also that when in -15°C, they would prefer the ambient temperature to be warmer. As for 5°C, the subjects preferred the ambient temperature to be neutral and at the end of the trial, to be cooler (figure 9). The difference in PTS was significant between the temperatures. When subjects reported perceived thermal comfort, no significant differences between the two ambient temperatures was found (figure 10).

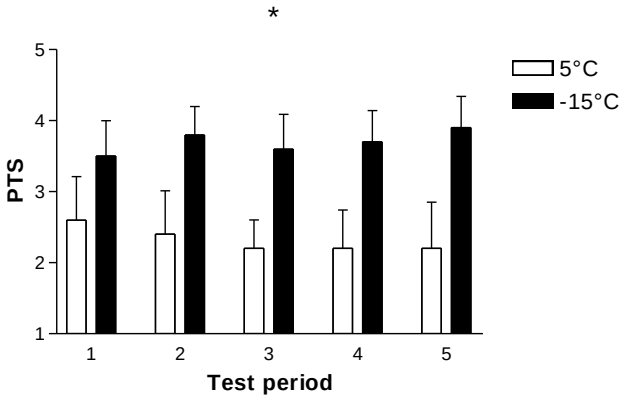

Fig. 9. Mean values (±SD) for perceived thermal sensation (PTS). N=15. The question was: How would you prefer the ambient temperature? The scale range; 1 is much cooler, 3 is neutral and 5 is much warmer. A significant difference in PTS was found between the temperatures.

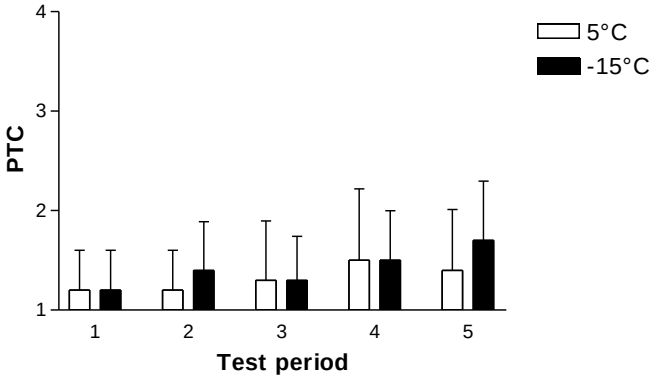

Fig. 10. Mean values (±SD) for perceived thermal comfort (PTC). N=15. The question was: How is your thermal comfort level? The scale range; 1 is comfortable, 4 is very uncomfortable. No significant differences was found between the temperatures in perceived comfort level.

NIRS

Group response

Figure 11 shows group response in HHb, tHb and O_2Hb during the last DWF in -15°C and 5°C.

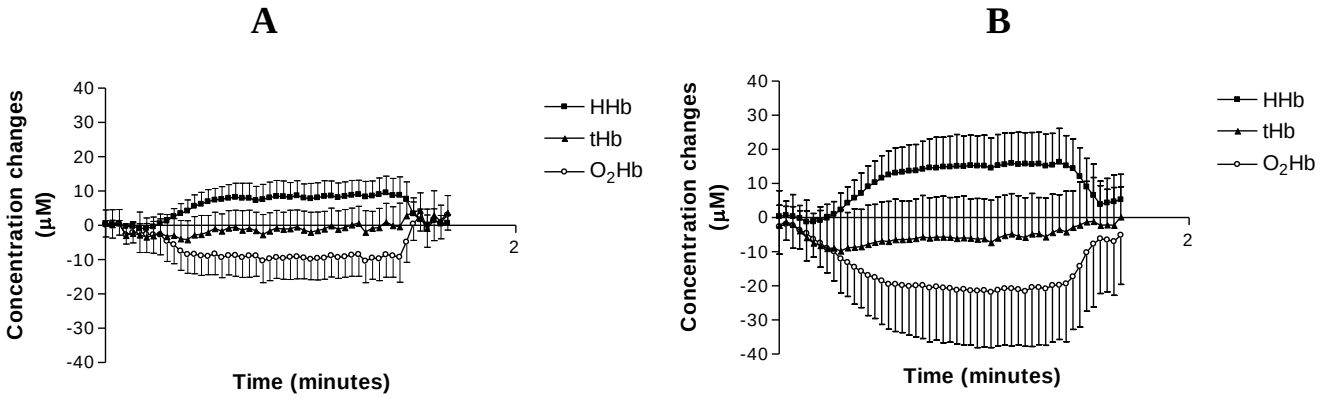

Fig. 11. Group response for O_2Hb, HHb and tHb during the last test period of two minutes of dynamic wrist flexion (DWF) in -15°C (A) and 5°C (B).

O_2Hb and tHb

There was a significant effect of temperature on oxyhaemoglobin (O_2Hb). There was a greater amount of oxygenated haemoglobin in the FDS in 5°C compared to -15°C (figure 12a). No significant effect of time was found. A similar result was found for deoxyhaemoglobin (HHb), with significant less deoxygenated haemoglobin during -15°C compared to 5°C. No significant differences in blood volume changes (tHb) (figure 12b) during DWF were found between 5°C and -15°C.

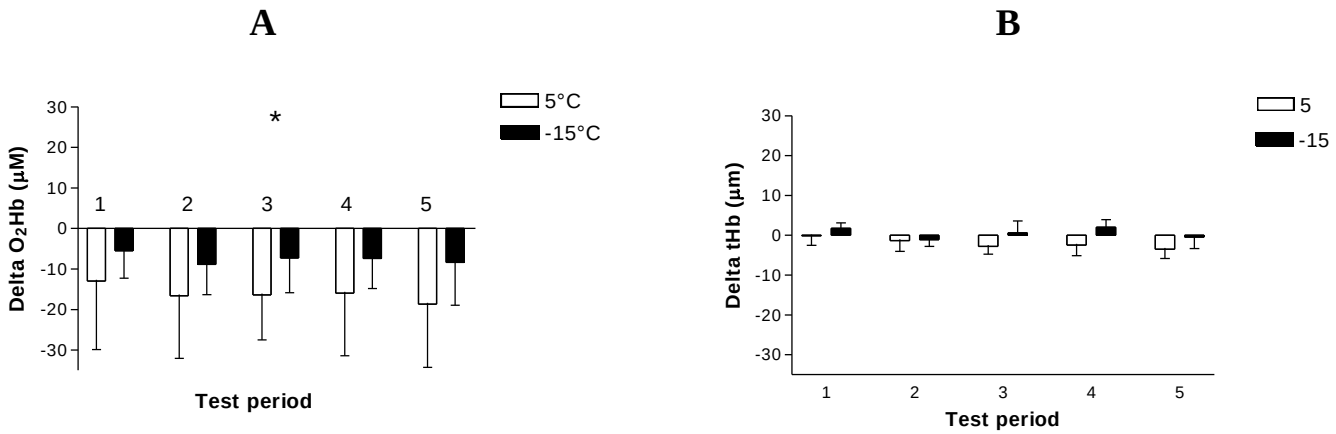

Fig. 12. Delta values for oxyhaemoglobin (O_2Hb) (A) and blood volume changes (tHb) (B). A significant effect of temperature was found in -15°C compared to 5°C regarding O_2Hb, but not for tHb. N=15.

Force

The subjects generated a peak torque during isometric wrist flexion MVC of about 300 N. Overall, there was no significant difference in isometric strength (N) between 5°C and -15°C (figure 13).

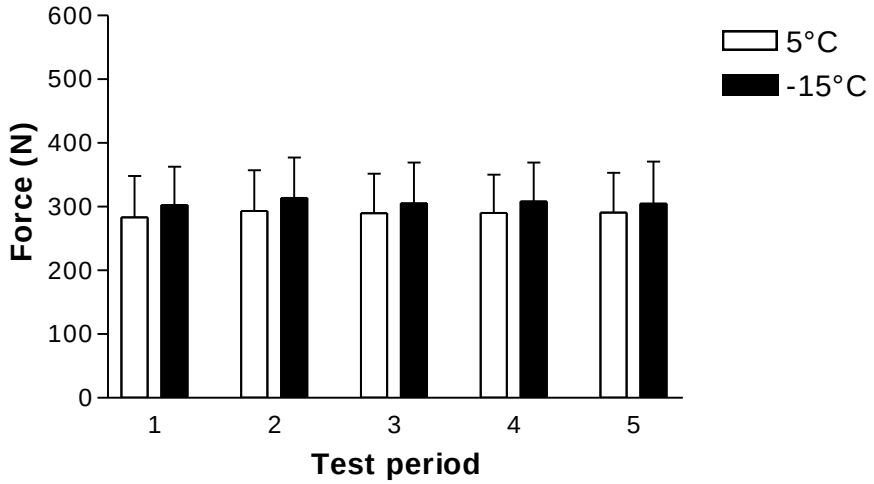

Fig 13. Peak torque during isometric wrist flexion MVC (N) from right wrist flexion. No significant difference between 5°C and -15°C. N=15.

EMG

EMG data is shown in amplitude, both normalized (percentage of max activation) and un-normalized (μV) data.

Flexor digitorum superficialis – EMG amplitude displayed as percentage of max activation

When the subjects were doing manual work with their arms above their head for five minutes, Normalized EMG records shows no significant difference in activation level in the right wrist flexors during 5°C compared to -15°C (figure 14). Activation level for the same muscle show no significant difference in normalized EMG data in the right wrist flexors during 5°C compared to -15°C (figure 14).

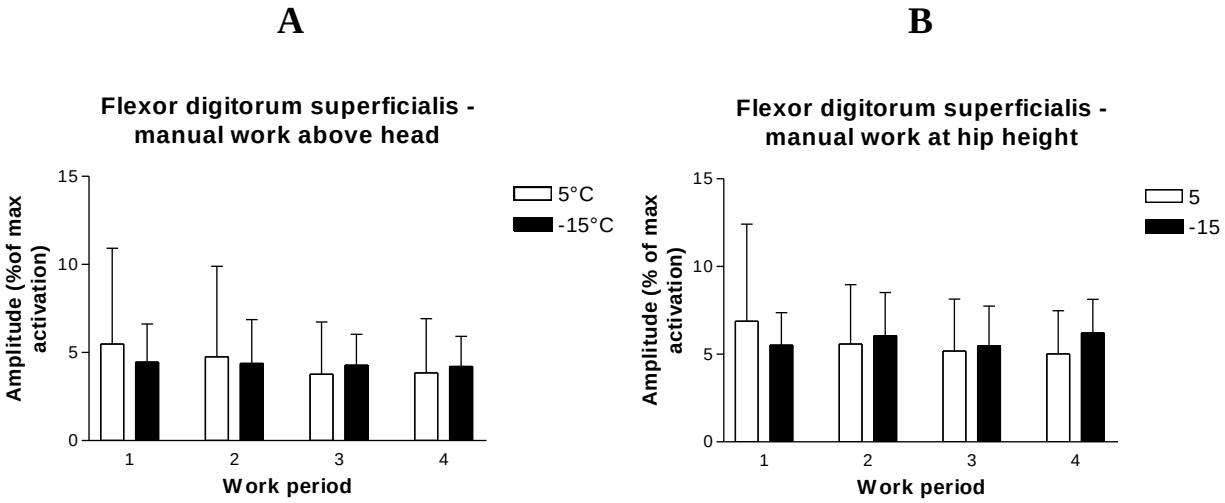

Fig. 14. Mean activation level (% of max activation) in right flexor digitorum superficialis: manual work above head for 5 minutes. N=13. No significant effect of temperature was found between the temperatures

Extensor digitorum – EMG amplitude explained as percentage of max activation

As for ED, activation levels in this muscle were not affected of temperature nor time. We found no differences between normalized EMG data in 5°C and -15°C in ED, when doing manual work above head and when working at hip height.

Flexor digitorum superficialis – EMG amplitude displayed as µV

When the subjects were doing manual work with their arms above their head for five minutes, there was a significant effect of time and temperature on amplitude on FDS during the three last work periods (figure 15a and 15b). The amplitude was significantly higher in -15°C compared to 5°C when working above head and when working at hip height. Amplitude decreases during the trial in 5°C, but persists in -15°C. There was also a significantly higher amplitude in FDS when working at hip height compared to when working above head.

Extensor digitorum – EMG amplitude displayed as µV

Regarding the right ED, we found no significant effect of temperature nor time (figure 15c and 15d). However, a significantly higher amplitude was found when working above head compared to working at hip height.

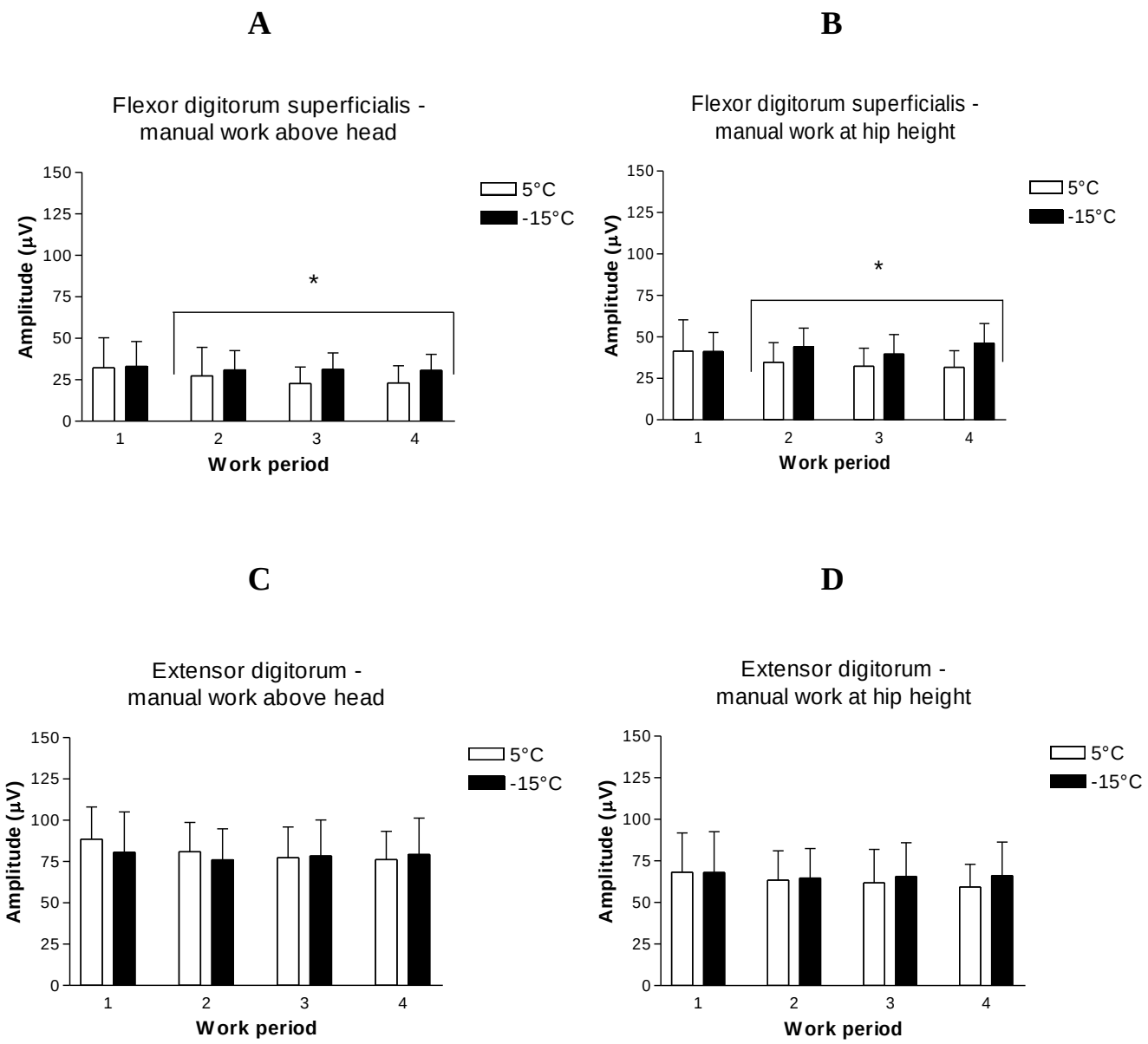

Fig. 15. EMG amplitude in FDS when working with arms above head (A) and EMG amplitude for the same muscle when working at hip height (B). EMG amplitude in ED when working with arms above head (C) and EMG amplitude for the same muscle when working at hip height (D). N=13. A significant effect of temperature and time was found between the two temperatures in FDS. No effects of temperature or time was found in ED.

DISCUSSION

The main results from this study was lower skin temperatures, higher wrist flexor activity and alterations in muscle metabolism at -15°C compared to 5°C We observed a smaller reduction in muscle oxygenation in -15°C and a higher EMG amplitude in FDS during manual work. The effect of cold was not observed for ED. Although the reduction in skin temperatures were rather small in a practical perspective, it is likely that the changes in skin temperature was sufficient to affect muscle function.

Thermal response

In our study, skin temperatures clearly demonstrated that superficial cooling was present in -15°C, especially in forearm, hand and finger. The subjects also reported that they were feeling colder in the peripheral tissue in this environment. Core temperature was however not affected by the thermal exposures, as well as the reported grade of thermal comfort; subjects were not feeling significant uncomfortable in -15°C due to cold compared to 5°C. However, the results showed that the subjects were feeling colder in -15°C than in 5°C. This is explained by a higher level of heat loss to the environment, resulting in lower skin temperatures. Hence, the subjects were feeling cold, but only on a superficial level.

We did not measure actual muscle temperature, but skin temperature measurements is an indirectly measure of muscle temperature (Oksa et al. 1997) and local forearm skin temperatures of 29–35°C suggest that changes in actual muscle temperature are small (Clarke et al. 1958). Wiggen et al. (2010) investigated manual performance and thermal responses during low work intensity in persons wearing standard protective clothing used in the petroleum industry when they were exposed to a range of temperatures (5, –5, –15 and –25°C). They found that exposure to –5°C or colder lowered skin and body temperatures and reduced manual performance during low work intensity. Forearm skin temperatures differed between 29–35°C, which can be related to the forearm temperature fluctuations in our study. Wiggen et al. (2010) concluded that finger skin temperature below 20°C would result in impaired manual performance.

Oksa et al. (2002) performed a study consisting of eight men who performed six 20-min work bouts at thermo neutral (25°C) and cold (5°C) environments while exposed to systemic and local cooling. The tasks were wrist flexion-extension exercise at 10% of MVC. Average

muscle temperature (measured at 0.5cm depth) during systemic cooling and local cooling in this study was 30.0 ±0.6°C and 30.3 ± 0.8°C respectively. These muscle temperatures are directly related to our findings in forearm skin temperature. Further, Oksa et al. (2002) demonstrated that during low intensity repetitive work in cold environments, stretch reflex responses increase. This clearly shows that the increased strain of the working muscles are met by an increase in the reflex activity. Therefore, in cold environments, the muscles recruit more muscle fibres in order to maintain the given work level. However, the subjects wore insulated clothes, but with the hand sleeve cut off. We did a systemic cooling in our study with whole body covered with protective clothing, similar to a realistic scenario. Even though the subjects were exposed to warmer conditions, forearm temperature in our study was only 0.9 °C higher compared to Oksa et al. (2002). Our results regarding forearm temperature and increased EMG activity in the forearm are in line with Oksa et al. (2002).

Our findings in skin and core temperature can be related with these previous studies regarding temperature and clothing. Wiggen et al. (2010) demonstrated that when doing manual work and wearing protective clothing, skin temperature fell as ambient temperature decreased along with impairments in manual work. Oksa et al. (2002) found that systemic cooling of the body and local cooling of the forearm in 5°C lead to decreased skin temperatures, and thus enhanced muscle activity, increased level of coactivation and enhanced fatigue in forearm muscle compared to thermo neutral conditions.

Muscle function

Muscle oxygenation

The effect of cooling that was found in using NIRS was less deoxygenation in FDS during two minutes of DWF in -15°C compared to 5°C. Accordingly, we found a smaller reduction in oxygenation in FDS in -15°C compared to 5°C. Our results demonstrate that less oxygen was saturated in the muscle in the cold environment. There was no significant difference in tHb levels. Changes in tHb can be interpreted as changes in blood volume in the tissue (Van Beekvelt et al. 2001). Thus we may assume that there was no difference in the amount haemoglobin between the tests. In a review by Racinais & Oksa (2010), the authors demonstrated that during short duration exercise, there was a positive relationship between performance and muscle temperature. Neuromuscular function is impaired by low temperature and improved by hot temperature. The variation in performance ranged from two

2-5% both ways. Berg & Ekblom (1979) concluded that as little as one degree change in muscle temperature is enough to reduce or improve muscle performance in exercises as ball throw, cycle power, leg force and vertical jump. However, this effect will cease if hyperthermia occurs (Racinais et al. 2008). This effect was more marked for fast than slow movement. The physiological results of such cooling are peripheral muscle failure due to reduced blood flow in the tissue and to some extent failure in the transmission of the neural drive (Racinais et al. 2008). Since NIRS measurement concentrations primarily change in the small vessels (<1mm), the volume of blood measured by NIRS is most likely decreased during cooling due to vasoconstriction in these vessels. Hence, changes in O_2Hb and HHb will most likely be less pronounced under such conditions as was found in our study. A study made by Tew et al. (2010), differentiated between skin blood flow (laser flowmetry) and NIRS saturation, and found that the reliability of NIRS saturation measurements was good. However, we have inadequate literature of the use of NIRS in cold exposures. The knowledge of use of NIRS to investigate muscle oxygenation in cold environments is limited, and further studies are needed to confirm or disprove our findings on this matter.

Further, we detected that oxygenation values was lower in -15°C than in 5°C already after three minutes of cold exposure. This effect was also apparent on individual level. One possible theory is that the effect of cold was seen very early in the peripheral microcirculation, and that oxygenation values dropped already after the first test period. However, the subjects were wearing cold protective clothing, and thus it is not reasonable that the effect of cooling occurs after such short time of exposure. Forearm temperature after three minutes of exposure to 5°C showed to be 32.2°C. Compared to -15°C, forearm skin temperature after three minutes was one degree lower. The NIRS signals are measured at a depth of approximately 17.5mm in the tissue. Oksa et al. (1993) demonstrated that forearm muscle temperature during exposure to a 10°C water bath, was higher at 30mm skin depth compared to 20mm depth. According to Oksa et al. (1993), we may assume that the tissue is warmer than the measured skin temperature, and that the cold has not reached 17.5mm depth at this point. However, we have no methodical reason to believe that our findings are incorrect. In spite of this, the measured NIRS data are uncertain and it is difficult to draw plausible conclusions from the measurement.

Isometric muscle strength

We found no changes in force output (N) in isometric strength in our study, which are in line with previous results. Earlier studies have demonstrated that the main cause of alterations in muscle force is changes in muscle temperature. However, in comparison with dynamic force production, isometric force production is only slightly temperature-dependent at muscle temperatures of 25–35°C (Wiggen et al. 2010). Previous studies have demonstrated that a reduced muscle temperature may be favourable for isometric MVC (McGown 1967). On the other hand, literature quite uniformly reports that with muscle temperatures below 27°C, isometric MVC decreases, and the decrement being within the range from 11 to 19 % (Barnes, 1983, Buller et al. 1984, Coppin et al. 1978). Wiggen et al. (2010) found no significant differences in grip strength in ambient temperatures ranging from 5°C to -25°C while wearing protective clothing. This type of work can be related to the isometric wrist flexion test that our subjects performed in this study. Forearm temperature in our study did not fall below 30°C. According to mentioned studies, our findings are in line with those who did not detect any changes in isometric strength, probably because of an insufficient lowered forearm temperature.

Muscle activity

In the present study, a higher EMG amplitude was found in -15°C in FDS compared to 5°C. Two hours cold exposure with realistic work-related tasks and protective clothing, led to a higher muscle activation in the three last work periods compared to 5°C in FDS. In general, the FDS became more effective in 5°C compared to -15°C. This is probably an effect of the lowered skin temperatures, whereas forearm temperature was almost 2°C lower in -15°C than in 5°C. This indicated that compared with manual work in 5°C, the condition of -15°C causes increased muscle activity. We may assume as previous studies have stated (Petrofsky et al. 1979, Winkel & Jørgensen 1991, Wolf et al. 1975) that this decrease in skin temperature during manual work, leads to mechanisms as decreased motor unit firing frequency increased co-activation and increased reflex activity. This results in an increased level of the agonist-antagonist muscle pairs and thus an earlier case of fatigue in the FDS. This is probably why we see this higher amplitude in -15°C during manual work compared to amplitude in 5°C.

Earlier findings have demonstrated that EMG amplitude increases as muscle temperature decreases at a given submaximal workload (Oksa et al. 2002, Racinais et al. 2010, Bergh & Ekblom 1979). It is also reported rather uniformly that cooling decreases the frequency of

EMG (Petrofsky et al. 1979, Winkel & Jørgensen 1991, Wolf et al. 1975), and that the decrement seems to depend rather linearly on the level of cooling (Petrofsky et al. 1979). For example, a 30 min exposure of the forearm to 10°C water in relation 40°C water decreased the motor unit firing frequency from approximately 180 Hz to 100 Hz and increased reflex activity in the muscle during brief and sustained isometric contractions (Petrofsky et al. 1979). Oksa et al. (1993) demonstrated that if muscle temperature of triceps brachii and deltoideus (measured at 30mm depth) was decreased from 32.1°C ± 0.8 and 33.4°C ± 1.2 respectively by only 1.8°C, this led to a significant decrease in muscle performance. Muscle performance in study was measured as velocity and length of ball throw. Oksa et al. (2002) claims that when muscle decrease, it works more inefficient, and reaches fatigue earlier compared to a higher muscle temperature.

Further, there was an effect of temperature on FDS, but not ED. Apparently, the effect was muscle dependent. When we only detected a significant higher amplitude on FDS but not for ED, we might assume that the effect of temperature seen on FDS is rather small. Most likely would both muscles be affected by the cold if the effect of temperature on forearm muscles were substantial. It would also make the current findings more reliable. It is difficult to conclude that the demonstrated differences in oxyhaemoglobin/deoxyhaemoglobin (NIRS), were the actual cause of the increase in amplitude found in FDS. EMG amplitude was measured at the right FDS during manual work, and NIRS was measured at the left FDS during DWF. Thus, additional studies are needed to investigate how oxygenation/deoxygenation affects muscle activity in a more direct matter during the same work. In this study, one may only assume that there is a link between higher EMG amplitude in FDS during manual work and a reduced deoxygenation in FDS during DWF.

Methodical limitations of EMG analysis, is that the amplitude is influenced by the given detection condition. It can vary between electrode sites, subjects and even day-to-day measures of the same muscle site. This causes variation, but not significant differences. Thus could this effect be a confounder in the present study. One solution to overcome this "uncertain" character of micro-volt scaled parameters is the normalization to reference value, e.g. the maximum voluntary contraction (MVC) value of a reference contraction (Konrad, 2006). However, this MVC value was different between the temperatures. This kind of normalization of data is therefore dependent of the subject's ability to perform a correct MVC to get proper normalization to reference values. It look like this was a problem, when normalized data shows entirely different data compared to un-normalized.

Our results on the effect of low skin temperature and increased EMG amplitude during manual work is in line with previous studies.

Limitations

Most of our subjects were young men, so the presented data herein may not be generalizable to other gender- or age groups. Even though the subjects were a relatively homogenous group, there was a tendency that the larger subjects felt comfortable in the cold environments, and the smaller subjects felt less comfortable. On the contrary, the same tendency shows that the larger subjects felt uncomfortable in the warmer condition. In real life, however, small and large individuals will be expected to carry out similar work tasks.

EMG and NIRS was measured on different arms and analyses were performed when doing different tasks (NIRS during DWF, EMG during work above head and at hip height). There would be an advantage if it was possible to measure NIRS and EMG on the same arm. In the future, it is possible to investigate changes in O_2Hb and tHb values in this dataset during work periods and compare data with already known EMG results. Further, when the subjects were working with the respective tasks, it is difficult to know whether the FDS or ED muscles were functioning as agonists or antagonists during these given work tasks. It would most probably be easier to distinguish between the exact movements if we had used an accelerometer in this study. EMG in general are easier to interpret when this sort of equipment is available.

CONCLUSION

The main findings of this study were that the conditions in this study led to lower finger and forearm skin temperatures in -15°C compared to 5° C. Further, when the subjects were exposed to -15°C, this resulted in a smaller reduction in oxygenation in FDS and a higher EMG amplitude in the same muscle compared to 5°C. We did not detect the same effect of temperature on ED, nor any effects of cold on isometric strength in wrist flexion. The subjects were not feeling significant uncomfortable in -15°C compared to 5°C, but reported that they were feeling colder on hands and feet in -15°C

The conditions in this study did not cause detrimental effect on muscle function. In conclusion, cold exposure reduced skin temperatures, which further led to minor negative effect on muscle function.

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Appendix 1 – Thermal questionnaire

Name:_____Date:_____5/-15:_____

HVORDAN FØLER DU DEG TERMISK DIN:	1	2	3	4	5
1. KROPP					
2. FØTTER					
3. HENDER					
4. HODET					

-5 = ekstremt kald
-4= svært kald
-3=kald
-2=kjølig
-1=litt kjølig
0= nøytral
5 = ekstremt het
4 = svært het
3 = het
2 = varm
1 = litt varm

HVORDAN VIL DU FORETREKKE OMGIVENDE TEMPERATUR?	1	2	3	4	5
1. MYE KJØLIGERE					
2. LITT KJØLIGERE					
3. NØYTRAL					
4. LITT VARMERE					
5. MYE VARMERE					

HVORDAN FØLER DU DEG TERMISK TILPASS?	1	2	3	4	5
1. KOMFORTABEL					
2. LITT UKOMFORTABEL					
3. UKOMFORTABEL					
4. SVÆRT UKOMFORTABEL					