

# Effect of Cold Conditions on Manual Performance while Wearing Petroleum Industry Protective Clothing

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**Abstract:** The purpose of this study was to investigate manual performance and thermal responses during low work intensity in persons wearing standard protective clothing in the petroleum industry when they were exposed to a range of temperatures (5, -5, -15 and -25°C) that are relevant to environmental conditions for petroleum industry personnel in northern regions. Twelve men participated in the study. Protective clothing was adjusted for the given cold exposure according to current practices. The subjects performed manual tests five times under each environmental condition. The manual performance test battery consisted of four different tests: tactile sensation (Semmes-Weinstein monofilaments), finger dexterity (Purdue Pegboard), hand dexterity (Complete Minnesota dexterity test) and grip strength (grip dynamometer). We found that exposure to -5°C or colder lowered skin and body temperatures and reduced manual performance during low work intensity. In conclusion the current protective clothing at a given cold exposure is not adequate to maintain manual performance and thermal balance for petroleum workers in the high north.

**Key words:** Finger dexterity, Petroleum work, Cold, Manual performance, Protective clothing

## Introduction

Petroleum workers are often exposed to harsh and extreme environments and their work requires manual skills regardless of environmental conditions. Typical work tasks include heavy lifting, tool handling and the assembly of small nuts and bolts, and many of these tasks demand fine and gross manual dexterity and grip strength. The growth in petroleum industry activity in the circumpolar region means that we need better knowledge of the effect of cold on the performance of this occupational group.

Petroleum workers with the existing protective clothing may need to remove their gloves in order to per-

form specific tasks. Removing the gloves accelerates cooling of the hands. Exposure to cold is known to reduce manual performance and increase the risk of human errors<sup>1</sup> that may have fatal consequences for the environment and human health. Manual performance is related to finger ( $T_{fi}$ ) and hand ( $T_{ha}$ ) skin temperatures<sup>2</sup>. Clark<sup>3</sup> reported reduced manual performance at a  $T_{ha}$  of 13°C. A thorough review from Heus *et al.*<sup>2</sup> suggests that a minimum decrease in manual performance occurs at  $T_{ha}$  and  $T_{fi}$  of 20°C and severe loss of manual performance at  $T_{ha}$  and  $T_{fi}$  at 15°C and below. Cooling has been reported to impair joint movement as a result of increased viscosity of the synovial fluid and tissues of the hand<sup>4</sup>. Further local cooling of hands and arms can affect muscle activity through a decrease in ATP utilization, enzyme activity, slowed calcium and acetylcholine release and delayed cross-bridge forma-

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tion<sup>2, 5, 6</sup>). These alterations lead to decreased contraction velocity, and reduced maximal strength and time to exhaustion<sup>2</sup>.

Several studies have focused on which physiological parameters are the primary determinants of loss of manual performance. These parameters have been  $T_{ha}$  and  $T_{fi}$ , body heat content ( $H_b$ ) and changes in body heat content ( $\Delta H_b$ )<sup>7–10</sup>. Gaydos and Dusek<sup>10</sup> looked at the effect of local versus total body cooling and concluded that  $T_{fi}$  seemed to be the primary determinant of impaired manual performance. Brajkovic *et al.*<sup>8</sup> found a linear relationship between  $\Delta H_b$  and  $T_{fi}$ . They further showed that  $\Delta H_b$  is a better indicator of relative changes in extremity temperature and finger dexterity than rate of body heat storage. Brajkovic *et al.*<sup>7</sup> tested the effect of direct hand heating (heated gloves) and indirect heating (heated vest). They found that during three hours of exposure to  $-25^\circ\text{C}$  it is possible to maintain finger dexterity by means of both indirect and direct hand heating in spite of a negative rate of body heat storage during direct hand heating.

A study by Flouris *et al.*<sup>9</sup> supports the findings of Brajkovic *et al.*<sup>7, 8</sup>, and further showed that not only maintaining  $H_b$  during work but pre-heating before cold exposure is effective in maintaining hand function. Flouris *et al.*<sup>9</sup> also showed that  $\Delta H_b$  was the best indicator of hand function followed by  $T_{fi}$ . These findings demonstrate that decrements in manual performance are not due to reduced skin temperature alone, but are rather a result of changes in several variables.

To the best of our knowledge no studies have focused on the effect of cold exposure on manual performance under conditions of protective clothing relevant to petroleum workers. Previous studies on the effect of cold exposure on manual performance have focused on military clothing<sup>7–9, 11</sup> and nuclear, biological and chemical (NBC) protective clothing<sup>12</sup>. Hence, we do not know whether the clothing used by petroleum workers provides sufficient protection against cold.

Some studies were designed to investigate a specific physiological phenomenon e.g. hand cooling while the rest of the body is at room temperature<sup>13</sup>, or the opposite case: cooling the core while maintaining hands warm<sup>14</sup>. In spite of well established understanding of how cold conditions influence manual performance, our

knowledge of how cold affects more specific operational tasks and thermal responses with realistic clothing in petroleum workers is still sparse.

The aim of this study was to investigate manual performance and thermal responses in test persons wearing standard protective clothing for petroleum workers when they were exposed to a range of temperatures relevant to the prevailing environmental conditions for petroleum industry in northern regions. We wished to acquire a better understanding of the effects of such temperatures on manual performance and thermal responses for relevant work-specific manual tasks during a typical work shift. We hypothesized that exposure to cold under these conditions would lead to lowered  $T_{ha}$ ,  $T_{fi}$  and  $H_b$  together with reduced thermal comfort when wearing standard protective clothing for petroleum workers. We further hypothesized that such  $T_{ha}$  and  $T_{fi}$ , together with lowered  $H_b$  would lead to reduced hand and finger dexterity.

## Subjects and Methods

### Subjects

Twelve male subjects participated in the study (Table 1). The subjects had been informed of the aims of the project and had given their written consent. The study was performed according to the Helsinki Declaration and was approved by the regional medical research ethics committee.

Inclusion criteria were healthy male between 18 and 35 yr of age, a height of 170–190 cm, fat percent  $\leq 16\%$ . Exclusion criteria were earlier cold-related injuries or Raynaud's syndrome. These criteria were selected with the aim of obtaining a highly homogeneous group. During the test the subjects were instructed to rest quietly in a sitting position in order to minimize metabolic heat production. This enabled us to simulate a worst-case scenario with a minimum heat production rate and to make recommendations based on this scenario.

### Climatic conditions

All the participants underwent four exposures to cold ambient temperature ( $T_a$ ) of 5,  $-5$ ,  $-15$ ,  $-25^\circ\text{C}$  (air velocity 0.05 m/s) and one control exposure to normal

**Table 1. Physical characteristics of subjects. Data are means  $\pm$  SD.  $VO_{2max}$ , maximal oxygen consumption; BSA, body surface area is calculated according to Dubois and Dubois<sup>28</sup>)**

Age (yr)	Weight (kg)	Height (cm)	BSA (m <sup>2</sup> )	Fat (%)	$VO_{2max}$ (mL·kg <sup>-1</sup> ·min <sup>-1</sup> )
23 $\pm$ 1.8	77 $\pm$ 8	182 $\pm$ 4	1.97 $\pm$ 0.1	12 $\pm$ 2	64.0 $\pm$ 5.1

room temperature 22°C (air velocity 0.05 m/s). All the experiments were performed in a randomized order in a climatic chamber.

*Clothing*

The participants wore commercially available clothing typically used in the petroleum industry. These clothing ensembles are approved according to BS EN 533:1997<sup>15)</sup>, BS EN 471:2003<sup>16)</sup> for the outerwear and BS EN 531:1995<sup>17)</sup> for the inner and middle layers. Different clothing ensembles were used for all climatic conditions. Each clothing ensemble was based on observations and interviews regarding what are actually worn in the field. A thermal manikin was used to establish Clo-units<sup>18)</sup> value for each complete ensemble (Table 2). A Clo-unit is an expression of the insulation capacity provided by either one piece or a total clothing ensemble (1 Clo unit = 0.155 m<sup>2</sup> K/W).

*Manual dexterity determination*

During the experiment the subjects performed a manual dexterity test battery every 15 min. The test battery consisted of a tactile sensation test, Purdue Pegboard test (PPB), Complete Minnesota Dexterity Test (CMDT) and grip strength.

Tactile sensation was tested using a Touch test evaluator (Semmes-Weinstein monofilaments). The test consisted of presenting a monofilament to the tip of the finger and pressing it against the skin until it buckled. The subjects reported on the occurrence of stimulation. The subjects were seated with closed eyes and their hands resting supine on their thighs during the tactile sensation test.

PPB is a widely-used test for fine finger dexterity, which has been shown to be reliable and valid<sup>19)</sup>. This test was chosen because it simulates typical finger dexterity tasks encountered in the petroleum industry. The Purdue Pegboard consists of two rows of small holes surmounted by four cups containing small metal pins, collars and washers. The subject had an assembly test whose aim was to perform as many assemblies as possible in one minute. An assembled unit consists of pin, washer, collar and washer. One point was awarded for each unit assembled on the board. The subjects were instructed to perform one trial with the emphasis on best performance.

The CMDT is well correlated with hand dexterity<sup>20)</sup>, and can be related to relevant hand dexterity tasks under petroleum work. The selected test was a two handed placing and turning test. The objective of the test was

**Table 2. Clothing concepts at each ambient temperature. Clo, clothing insulation value (1 Clo unit = 0.155 m<sup>2</sup> K/W)**

		Ambient temperature				
		22°C	5°C	-5°C	-15°C	-25°C
Underwear	- JanusPro antifiame rib sweater - JanusPro antifiame rib pants	- JanusPro antifiame rib sweater - JanusPro antifiame rib pants	- JanusPro antifiame rib sweater - JanusPro antifiame rib pants	- JanusPro antifiame rib sweater - JanusPro antifiame rib pants	- JanusPro antifiame rib sweater - JanusPro antifiame rib pants	- JanusPro antifiame rib sweater - JanusPro antifiame rib pants
Middle layer garments		-JanusPro terry fleece jacket	-JanusPro terry fleece jacket -JanusPro antifiame rib polo neck sweater -JanusPro interlock thermal pants	-JanusPro terry fleece jacket -JanusPro interlock thermal pants	-JanusPro terry fleece jacket	-JanusPro terry fleece jacket -JanusPro antifiame rib polo neck sweater -JanusPro interlock thermal pants
Outer garments		- Wenaas antifiame jacket - Wenaas antifiame pants	- Wenaas antifiame jacket - Wenaas antifiame pants	- Wenaas antifiame jacket - Wenaas antifiame pants	- Wenaas pyrokon parkacoat - Wenaas pyrokon overall	- Wenaas pyrokon parkacoat - Wenaas pyrokon overall
Protective head garments		- JanusPro balaclava - Peltor safety helmet	- JanusPro balaclava - Peltor safety helmet	- JanusPro balaclava - Peltor safety helmet	- JanusPro balaclava - Devold balaclava - Peltor safety helmet	- JanusPro balaclava - Devold balaclava - Peltor safety helmet
Gloves		Odin work gloves	Odin work gloves	Odin work gloves	Odin work gloves	Odin work gloves
Socks	- wool/lycra	- wool/lycra - wool/ polyamid/ elasthan -	- wool/lycra - wool/polyamid/ elasthan	- wool/lycra - wool/polyamid/ elasthan	- wool/lycra - wool/polyamid/ elasthan	- wool/lycra - wool/polyamid/ elasthan
Shoes		Skolett Forma Work shoes	Skolett Forma Work shoes	Skolett Forma Work shoes	Skolett Forma Work shoes	Skolett Forma Work shoes
Clo	1.18	2.49	2.72	4.20	4.27	

to move all blocks from one board to another using both hands. Performance is measured in seconds and a higher score on the CMDT is an indication of reduced performance, i.e. a longer time taken to complete the task.

Grip strength was measured using a custom grip-strength dynamometer. The distance between the handlebars was set at 6 cm. Force was measured by a strain gauge sensor (Ergotest Technology A.S., Langesund, Norway) when the subject was seated with his arm in a standardized position.

#### Experimental protocol

In order to reduce the possibility of a learning effect during and between each test series the subjects underwent a thorough familiarisation process before the start of the study. Before each temperature exposure, each subject was familiarised with the PPB and fitted with the thermistors and then sat for 20 min to stabilize temperatures while wearing the 22°C clothing ensemble. Any additional clothing depending on exposure temperature was then put on according to current practices. When the subject entered the climatic chamber he immediately started the first test cycle, which comprised the tactile sensation test, the PPB test, CMDT, subjective thermal comfort and finally grip strength. The order of manual tests was the same under all cycles and ambient conditions. The gloves were removed before the tactile sensation test and put on again before the grip strength test, a total of 7 min without gloves at each test cycle. Between tests the subject was instructed to gently clench his fist which is a typical reaction to exposure to cold.

After the test-series the subject sat and remained seated until the next test cycle. During the rest period metabolic heat production was measured. There were five test cycles of 8 min and a total exposure time of 108 min for each subject at each ambient temperature. Only one test subject was in the climate chamber at a time.

#### Physiological variables

Skin temperatures were measured using thermistors

(YSI-400 Yellow Springs Instrument, USA, accuracy  $\pm 0.15^\circ\text{C}$ ). Thermistors were placed on the forehead, chest, back, upper arm, forearm, front of thigh, back of thigh, front of lower leg, foot and hand. Mean skin temperature ( $T_{\text{sk}}$ ) was calculated using a modified version of Teichner *et al.*<sup>21</sup>). A thermistor was also placed on the ring finger of the left hand ( $T_{\text{fi}}$ ). Rectal temperature ( $T_{\text{re}}$ ) was measured by a thermistor probe (YSI-700 Yellow Springs Instrument, USA, accuracy  $\pm 0.15^\circ\text{C}$ ) inserted 10 cm beyond the anal sphincter. All temperatures were recorded at 15-s intervals and continuously displayed on a monitor, to enable the thermal state of the subjects to be monitored throughout the experiment.

Heart rate ( $f_c$ ) was recorded by a Polar Sport Tester (Polar Electro, Finland). Oxygen consumption was measured over a five-minute period several times (Table 3) during the experiment by means of an Oxycon Pro (Cardinal Health, Germany). Metabolic heat production was calculated according to ISO 8996<sup>22</sup>).

#### Termination criteria

The experiment was terminated if the rectal temperature fell below 35°C and if one of the skin temperatures fell below 8°C. These criteria were chosen to reduce the risk of cold related injuries for the test persons. When termination criteria were reached the subject was immediately removed from the cold.

#### Statistical analyses

The statistical analyses were performed using SPSS 16.0 (Statistical Package for the Social Sciences, Chicago, Illinois, USA). Parametric tests were used since QQ-plots supported the assumption of normally distributed data. One-factor repeated measures of within-subjects analysis of variance (ANOVA) was used to determine changes over time at each  $T_a$ . Two-factors within-subjects ANOVA was used to determine changes between  $T_a$  and time. All analyses were performed using Bonferroni adjustments for repeated measures. Non-parametric tests were performed on the subjective evaluation scores because the data were at the ordinal level. Friedman's test was used to determine the effect of  $T_a$  and time on subjective evaluation score and

**Table 3.** Experimental protocol. Cycle, test cycle; Interval, test duration (min); Time, start time at each cycle; R, rest; C, put on required clothing; MT, manual tests; MH, metabolic heat production

	Pre		108 min of exposure to 22, 5, -5, -15 and -25°C												
Cycle	1		2			3			4			5			
Test	R	C	MT	R	MH	MT	R	MH	MT	R	MH	MT	R	MH	MT
Interval	20	10	8	11	6	8	11	6	8	11	6	8	11	6	8
Time	0		38			63			88			113			

Wilcoxon's was used to determine changes over time at each  $T_a$ . Pearson's correlation was used for analysis of correlations of  $T_{fi}$  with hand and finger dexterity. All data in tables are presented as mean and standard deviation (SD). In the figures the data are presented as mean and standard error (SE). Data were accepted as statistically significant at  $p < 0.05$ . Due to a high drop-out rate of subjects at  $T_a$  of  $-25^\circ\text{C}$  descriptive statistics have been used to describe the results.

**Results**

At ambient temperatures of  $-15^\circ\text{C}$  and  $-25^\circ\text{C}$  only ten and five subjects respectively completed all the tests. The drop-outs were due to a finger temperature of lower than  $8^\circ\text{C}$ . At  $-15^\circ\text{C}$  the subjects dropped out after 74 and 81 min of cold exposure. At  $-25^\circ\text{C}$  they dropped out after 31, 49, 54, 79, 80, 81 and 83 min of cold exposure.

*Finger and hand dexterity*

There was a significant effect of exposure time on PPB performance at  $-5^\circ\text{C}$  and  $-15^\circ\text{C}$ . Figure 1 shows the finger and manual dexterity scores for each ambient temperature and cycle. Compared to the control condition, temperature had a significant effect ( $p < 0.01$ ) on PPB performance at  $-5$  and  $-15^\circ\text{C}$ .

At  $-5$  and  $-15^\circ\text{C}$  there was a significant effect ( $p < 0.01$ ) of exposure time on CDMT performance. The time course of the development of the difference is shown in Fig. 1. Temperature had a significant effect ( $p < 0.01$ ) on manual performance at  $-5$  and  $-15^\circ\text{C}$ , compared with the control condition.

*Grip strength*

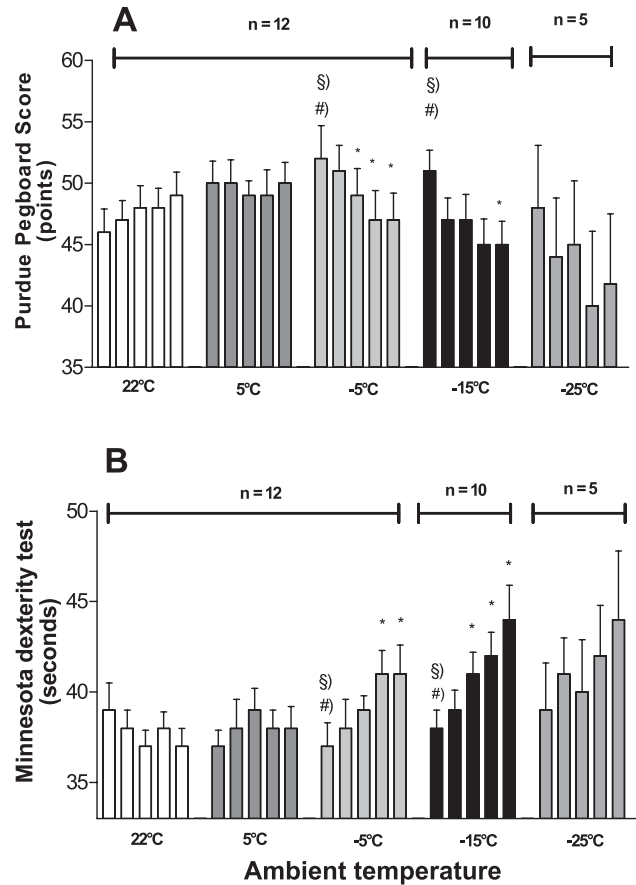
Overall, there was no significant effect of time on grip strength between the test cycles, nor any significant difference between the different temperature conditions. Mean measurements were  $542 \pm 75$ ,  $477 \pm 93$ ,  $471 \pm 83$ ,  $464 \pm 83$  and  $483 \pm 94$  Newton at 22, 5,  $-5$ ,  $-15$  and  $-25^\circ\text{C}$  respectively.

*Tactile sensation*

The tactile sensation test displayed no significant change over time at each  $T_a$ . However, there was a significant effect of both  $T_a$  and duration of exposure between  $22^\circ\text{C}$  and  $5^\circ\text{C}$  and  $-5^\circ\text{C}$ , with lowest sensation score of  $0.07 \pm 0$ ,  $0.09 \pm 0.03$  and  $0.11 \pm 0.06$  grams respectively.

*Metabolic heat production*

There was no significant effect of time or  $T_a$  on metabolic heat production which came to  $53 \pm 14$ ,  $57 \pm 7$ ,



**Fig. 1.** Purdue Pegboard score (A) and Complete Minnesota Dexterity Test (B) for ambient conditions  $22^\circ\text{C}$ ,  $5^\circ\text{C}$ ,  $-5^\circ\text{C}$ ,  $-15^\circ\text{C}$  and  $-25^\circ\text{C}$ . Bars are in order from left to right test cycles 1 to 5 for each ambient condition. Values are mean  $\pm$  SE for  $n=12$ , 10 and 5 as indicated. #) indicates significant effect of exposure time on score; §) indicates significant effect of ambient temperature compared to control; \* indicates significant difference compared to test cycle 1 under the same ambient conditions.

$59 \pm 11$ ,  $57 \pm 11$  and  $66 \pm 13$   $\text{W} \cdot \text{m}^{-2}$  at  $22^\circ\text{C}$  ( $n=12$ ),  $5^\circ\text{C}$  ( $n=12$ ),  $-5^\circ\text{C}$  ( $n=12$ ),  $-15^\circ\text{C}$  ( $n=10$ ) and  $-25^\circ\text{C}$  ( $n=5$ ) respectively. There was a difference in  $f_c$  over time at each  $T_a$ . The small variations in  $f_c$  appeared between the resting and test periods. There was no effect of  $T_a$  on  $f_c$ .

*Rectal temperature*

All exposures led to a decrease in  $T_{re}$ . After 108 min exposure total changes in  $T_{re}$  were  $-0.23 \pm 0.21$ ,  $-0.42 \pm 0.24$ ,  $-0.47 \pm 0.21$ ,  $-0.50 \pm 0.20$  and  $-0.55 \pm 0.57^\circ\text{C}$  at 22, 5,  $-5$ ,  $-15$  and  $-25^\circ\text{C}$  respectively. There were no significant differences between the different conditions. Due to missing data,  $n=11$  at 22 and  $-5^\circ\text{C}$ .



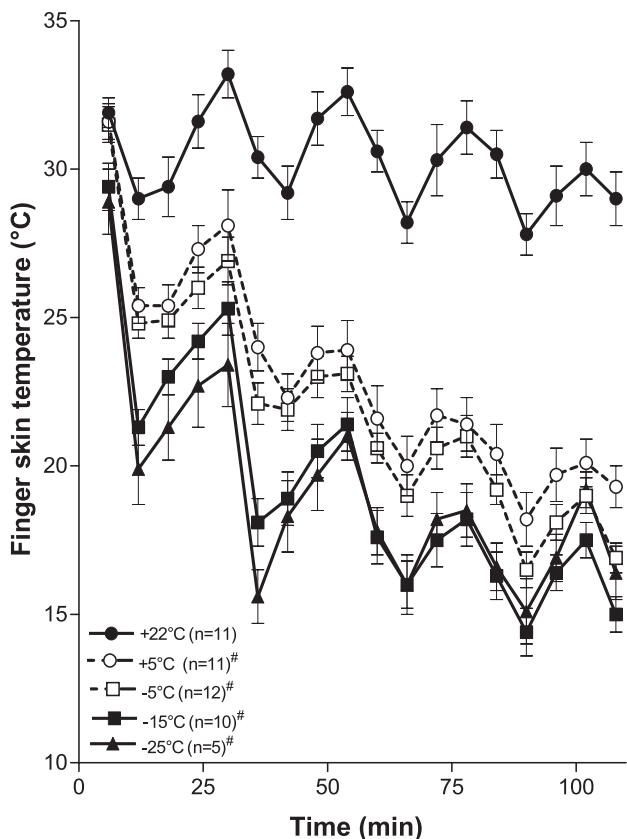


Fig. 2. Finger temperature for all  $T_a$ . #, indicates a significant effect of  $T_a$  compared to 22°C. Values are mean  $\pm$  SE.

*Skin temperatures*

$T_{sk}$  fell during cold exposure. The greatest reduction being during exposure to  $-5^\circ\text{C}$  and  $-25^\circ\text{C}$ , when it fell to  $-4.55 \pm 0.75$  and  $-4.81 \pm 1.26^\circ\text{C}$  respectively. We also found a significant difference ( $p < 0.01$ ) between the courses of temperature changes under the two conditions. There was an effect of both time and  $T_a$  on  $T_{fi}$  (Fig. 2). The large variations in  $T_{fi}$  are due to the gloves being removed for the manual tests.

*Body heat content*

$\Delta H_b$  showed a change over time for all  $T_a$ .  $\Delta H_b$  showed an effect of temperature (Fig. 3). A difference in  $\Delta H_b$  between  $T_a$  of  $-5^\circ\text{C}$  and  $-15^\circ\text{C}$  was also found.

We found a correlation ( $r=0.53$ ) between mean hand/finger dexterity and mean  $T_{fi}$  (Fig. 4). These values are average finger- and hand-dexterity scores with their respective  $T_{fi}$ , independent of  $T_a$  and time.

**Discussion**

This study has demonstrated that exposure to ambient temperatures of  $-5^\circ\text{C}$  or lower when wearing existing protective clothing such as is used in the petroleum

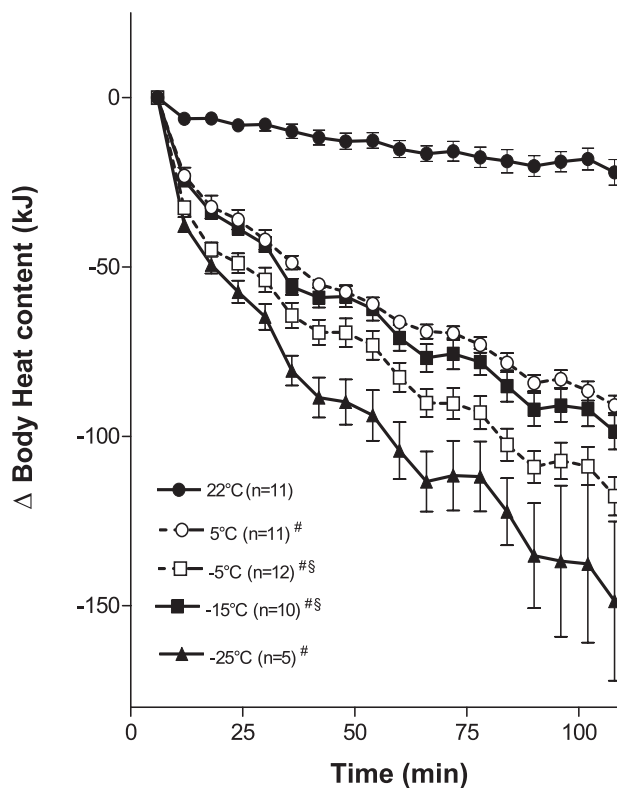


Fig. 3.  $\Delta H_b$  for each  $T_a$ . #, indicates a significant effect of  $T_a$  compared to  $+22^\circ\text{C}$ ; §, indicates a significant differences between  $-5^\circ\text{C}$  and  $-15^\circ\text{C}$ . Values are mean  $\pm$  SE.

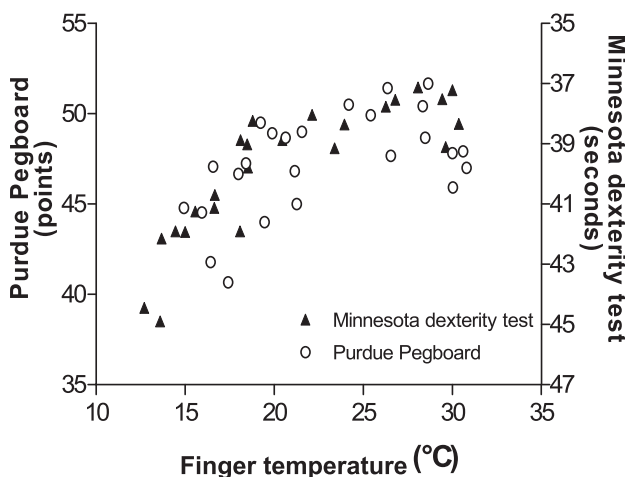


Fig. 4. Relationship between finger (Purdue Pegboard) and hand (Complete Minnesota Dexterity Test) dexterity with finger temperature. The values are means for each test cycle at all  $T_a$ .

industry leads to impaired manual performance. Cold exposure also reduces finger temperature, body heat content, and diminishes thermal comfort. These results confirm our hypothesis.

### Manual performance

Finger dexterity was reduced within 50 min of exposure to  $-5^{\circ}\text{C}$ , and after 100 min of exposure to  $-15^{\circ}\text{C}$ . These results show that even relatively short lasting exposures in a realistic work scenario can reduce the ability to perform finger and hand dexterity tasks. These findings are in line with Imamura *et al.*<sup>12)</sup>, who showed that manual performance, and finger dexterity in particular, were impaired after 40 min of exposure at  $-10^{\circ}\text{C}$  while subjects were wearing NBC protective clothing.

A study by Daanen<sup>11)</sup> estimated manual performance deterioration in the cold using the wind chill equivalent temperature (WCET), and established regression equations to calculate the drop in manual performance using WCET and duration of exposure. According to Daanen's equation, finger dexterity will be reduced by 8.9% at  $-15^{\circ}\text{C}$  after 25 min of exposure. We found that finger dexterity fell by 8.8% after the same cold exposure and duration. Insulation of clothing in Daanen<sup>11)</sup> was  $0.35\text{ m}^2\text{ K/W}$  without a parka and  $0.38\text{ m}^2\text{ K/W}$  with a parka. Recalculated, these values represent 2.26 and 2.45 Clo respectively, which is in the same range as the clothing concepts used in  $5^{\circ}\text{C}$  and  $-5^{\circ}\text{C}$  in our study. Our study, did not include wind chill but the thermal stress is in the same range and the effect of cold on manual performance was in line with the findings of Daanen<sup>11)</sup>.

We observed a reduction in finger and hand dexterity over time. Visual inspection of Fig. 4, which shows the relationship between finger and hand dexterity with finger temperature, suggests a drop at  $T_{\text{fi}} < 20^{\circ}\text{C}$ . These findings are in line with Schiefer *et al.*<sup>23)</sup> who found reduced manual performance at a  $T_{\text{fi}}$  of  $20\text{--}22^{\circ}\text{C}$ , and a more pronounced drop in performance at a  $T_{\text{fi}}$  of  $15\text{--}16^{\circ}\text{C}$ . In our study the low number of data-points at the lowest  $T_{\text{fi}}$  ( $T_{\text{fi}} < 15^{\circ}\text{C}$ ), can be explained with short finger skin exposure time and a high rate of cooling. The order of manual tests were standardized, where PPB and CMDT were performed second and third at each cycle which resulted in different  $T_{\text{fi}}$  between the tests. The high drop out number at the lowest ambient temperatures led to exclusion of the subjects with the lowest  $T_{\text{fi}}$ .

Reduced manual performance in the cold is not a result of any single factor, but rather of several contributing factors. Both finger and hand dexterity tests depend on rapid dynamic movements and require precise coordination of force in both time and space<sup>9)</sup>. Dynamic force production is highly temperature-dependent. 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<sup>24)</sup>. Furthermore lower tissue temperature has been shown to increase resistance in the finger joints and reduced mobility<sup>4)</sup>. Sekihara *et al.*<sup>25)</sup> have suggested that cold might also lead to a reduction in proprioception, which might be another contributor to impaired manual dexterity.

We found no changes in grip strength. The main cause of alterations in muscle force is changes in muscle temperature. In comparison with dynamic force production, isometric force production is only slightly temperature-dependent at muscle temperatures of  $25\text{--}35^{\circ}\text{C}$ . We did not measure forearm muscle temperature, but local forearm skin temperatures of  $29\text{--}35^{\circ}\text{C}$  suggest that changes in muscle temperature were small<sup>26, 27)</sup>.

### Thermal responses

The  $\Delta H_b$  increased as a function of  $T_a$  and duration of exposure. These changes are mainly related to lower  $T_{\text{sk}}$  and to some degree lowered  $T_{\text{re}}$ , which did not change between exposures to different ambient temperatures. However,  $T_{\text{re}}$  decreased over time under all cold conditions and also during the control condition. This might indicate some form of heat stress during fixing instruments and getting dressed prior to the experiment. The decreased rectal temperature cannot be regarded as cooling but more like a result of normal thermoregulation which returned rectal temperature to normal level. Furthermore, we observed a significant difference in  $\Delta H_b$  between  $-15^{\circ}\text{C}$  and  $-5^{\circ}\text{C}$ . This can be explained by the differences in the insulation value of light and heavy outerwear. Light outerwear emphasises improved mobility and comfort compared with heavy outerwear, which provides more insulation but at the cost of bulkiness. Flouris *et al.*<sup>9)</sup> tested the influence of  $H_b$  on hand function for 130 min at  $-20^{\circ}\text{C}$ . Using a clothing ensemble estimated at 3.6 Clo, they found a  $\Delta H_b$  of approximately  $-100\text{ kJ}$ , which is practically the same as in our study. However Flouris *et al.*<sup>9)</sup> found that  $\Delta H_b$  levelled off after 70 min, whereas we found that it dropped steadily throughout the whole period of exposure. These differences can be explained by an exercise period at the same time as the levelling off in the study by Flouris *et al.*<sup>9)</sup>. Brajkovic *et al.*<sup>8)</sup> showed a continuously change in  $\Delta H_b$  over time of between  $-300$  and  $-400\text{ kJ}$  after 120 min of exposure to  $-25^{\circ}\text{C}$  wearing clothing ensembles between 2.6 and 3.6 Clo. Both Flouris *et al.*<sup>9)</sup> and Brajkovic *et al.*<sup>8)</sup> were able to maintain an  $H_b$  during cold exposure using auxiliary heating and were thus therefore being able to maintain manual dexterity, while we found no correlation between finger/hand dexterity and  $\Delta H_b$ . However, there was a correlation between  $T_{\text{fi}}$  and finger/hand dexterity. This indicates that in real-life scenarios,  $T_{\text{fi}}$  might act as a good

indicator of manual performance.

At an ambient temperature of  $-25^{\circ}\text{C}$  there was a high drop-out rate due to  $T_{\text{fi}}$  being below  $8^{\circ}\text{C}$ . Only five subjects lasted for the whole exposure period of 108 min. The data presented here are therefore the means for these five persons. However, these subjects were able to maintain higher body and skin temperatures, unlike the dropouts which leads to an underestimation of the effect of cold on manual performance. Even though the subjects' physical characteristics were similar, there was a tendency for only the larger subjects to be able to complete the test protocol. In real life, however, small and large individuals will be expected to carry out similar work tasks. We might also mention that our population were only young men so the presented data herein may not be generalisable to other gender- or age-groups.

### Conclusions

During low work intensity the current protective clothing used at a given cold exposure leads to lowered body and skin temperatures, especially in the extremities, and to reduced manual performance when wearers are exposed to ambient temperature conditions of  $-5^{\circ}\text{C}$  or lower. Finger temperature was found to be an important indicator of hand and finger dexterity. This and previous studies suggest that a finger skin temperature below  $20^{\circ}\text{C}$  will result in impaired manual performance.

### Perspectives

Increased activity of the petroleum industry in the high north will involve working in a tougher climate and worse ambient conditions than used in this study. This presents major challenges to the petroleum industry and indeed all employers of personnel working outdoors in the high north. Body temperatures, heat content and manual performance need to be maintained at acceptable levels in order to ensure the health, safety and comfort of workers both offshore and onshore and maintain a high-quality work performance. The current observations might also be extended for other occupational groups with similar work tasks, protective clothing and work intensity for example construction workers. This study has shown that the current practices are not sufficient. Further effort needs to be put into developing better clothing concepts in order to maintain the health, safety, comfort and performance of this occupational group.

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