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Effect of working position and cold environment on muscle activation level and fatigue in the upper limb during manual work tasks

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ABSTRACT

Several occupational groups are exposed to periods of low ambient temperatures while performing manual work tasks outdoors. Work tasks typically include heavy lifting, tool handling, and overhead work. This study evaluated the effect of working position and cold environment on muscle activation level (%RMS$_{max}$) and fatigue in the upper limb during manual work tasks. Fourteen male participants (25 ± 3 years, 80.9 ± 6.4 kg, 182 ± 5 cm) completed a 2-h test protocol consisting of five test periods alternating with four work periods, wearing identical sets of clothing, under cold (−15 °C) and control (5 °C) conditions. The work periods consisted of manual work at the hip level, manual overhead work, and a lifting exercise. The test periods consisted of isometric maximal voluntary contractions (MVC) and seated rest. Skin temperatures decreased during cold exposure, especially in the extremities. %RMS$_{max}$ in the forearm was higher in the cold condition both during overhead work and work at the hip level than that for the same work in the control condition, especially at the end of the test when the difference was approximately 25% (equating to 2–3 %RMS$_{max}$). For the middle deltoid muscle, the %RMS$_{max}$ was approximately three times (or 10 %RMS$_{max}$) higher during overhead work than work at the hip level, but there was no additional cost of working in the cold. Signs of deltoid muscle fatigue (decrease in electromyography median power frequency and an increase in %RMS$_{max}$) were observed during the overhead work periods in both temperature conditions. No decrease in MVC, as a sign of overall muscle fatigue, was observed in either condition.

Relevance to industry: This study demonstrated that when wearing suitable cold-weather protective clothing, the adverse effect of work posture is much higher than that of cold on muscle demand and physical strain.

1. Introduction

Several occupational groups, such as industrial workers, miners, and petroleum workers, are exposed to periods of low ambient temperatures and harsh climatic conditions while performing manual work tasks outdoors. Work tasks typically include heavy lifting, tool handling, and overhead work. The occupational risk factors for developing musculoskeletal disorders include heavy physical work (da Costa and Vieira, 2010), manual material handling, and working with hands raised above the head level (Mayer et al., 2012). Furthermore, working in the cold appears to increase the incidence of musculoskeletal disorders compared with working in warmer environments (Chen et al., 1991; Piedrahita et al., 2004).

Exposure to moderately cold conditions has been found to increase muscle activation, thereby reducing the neuromuscular efficiency, in several upper extremity muscles during repetitive work in ambient temperatures of 4 °C–10 °C (Oksa et al., 2002, 2006, 2012; Piedrahita et al., 2008; Sormunen et al., 2009). However, the effects of repetitive

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Abbreviations: %RMS$_{max}$, muscle activity level; T$_a$, ambient temperature; DE, middle deltoid muscle; EMG, electromyography; HR, heart rate; MdPF, median power frequency; MVC, maximal voluntary contractions; PTS, perceived thermal sensation; RMS, root mean squared; RPE, rate of perceived exertion; T$_{sk}$, mean skin temperature; WH, work high; WL, work low; WP, work period.

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work in cold environments on wrist flexion muscle fatigue, measured as a decrease in force-generating capacity, differ between studies (Oksa et al., 2002, 2012). While maximal isometric work has been shown to have relatively low thermal dependence (Clarke et al., 1958; Oksa, 2002), it has been found that dynamic force production is highly temperature dependent, and even a slightly lower muscle temperature can influence the co-contraction of agonist–antagonist muscle pairs, and result in a "braking effect" and reduced muscle power (Racinais and Oksa, 2010).

At many work sites, the ambient temperature frequently decreases to below 0 °C and workers are required to wear cold-weather protective clothing to minimize heat loss from the body. In addition to adding protection, the clothing will increase the muscle demand and metabolic cost to the wearer (Dorman and Havenith, 2009; Renberg et al., 2020; Teitlebaum and Goldman, 1972), thereby increasing the total physical strain of working in the cold.

Overhead work, defined as working with hands raised above the acromion (Grieve and Dickerson, 2008), is a known occupational risk factor for developing musculoskeletal disorders. Myoelectric activity, measured using surface electromyography (EMG), is a common method of quantifying physical strain and neuromuscular fatigue associated with work. Several studies reported an increase in shoulder muscle activation on increasing shoulder angle during static work tasks (Brookham et al., 2010; Hellig et al., 2018). Moreover, prolonged repetitive manual tasks can cause muscle fatigue as indicated by increased muscle activation and decreased frequency content of the EMG signal (Qin et al., 2014). To reduce overload, it is suggested that if overhead work is unavoidable, it should be directed in front of and close to the body to decrease the muscular demand (Anton et al., 2001; Chopp et al., 2010; Maciukiewicz et al., 2016). The effect of overhead dynamic work, which is highly relevant in many occupational settings, is less studied than that of static tasks. To date, no study has investigated the combined effect of overhead work and cold ambient temperatures on muscle activity and fatigue.

To enable application of the general findings of this study to relevant scenarios in industrial settings, we designed a study that mimics a real work setting with dynamic work, a wide temperature range, and use of cold-weather protective clothing. The aim of this study was to evaluate the effect of working position and cold environment on muscle activation level and fatigue in the upper limb during manual work tasks. Therefore, shoulder and lower arm strength changes as well as wrist and deltoid muscle activation levels during overhead work and work at the hip level were investigated during cold exposure (2 h in −15 °C) and compared with those at a less cold ambient condition (2 h in 5 °C). Further, deltoid muscle fatigue development during the overhead work in the two ambient temperature conditions were investigated. We hypothesized that muscle activation level and fatigue would increase when performing dynamic work above the head level in the cold ambient temperature compared with dynamic work at the hip level and in the less cold ambient temperature resulting in decreased strength, increased muscle activation, and decreased frequency content of the EMG signal.

2. Material and methods

2.1. Participants

Fourteen healthy, trained males volunteered to participate in this study. Their mean age was 25 ± 3 years, body mass 80.9 ± 6.4 kg, height 182 ± 5 cm, and body fat 15.0 ± 1.8%. Consistent with the principles of the Declaration of Helsinki, the participants were informed about the test protocol and their right to withdraw from the experiment at any time before they provided their written informed consent. The study was approved by the Regional Committee for Medical and Health Research Ethics, North Norway.

2.2. Experimental design

The participants visited the research laboratory on three occasions. They were familiarized with the equipment and experimental protocol on the first visit, and their physical characteristics were measured (see *2.1. Participants*).

Tests were performed under cold (−15 °C) and control (5 °C) ambient conditions in an environmental chamber, in random and counterbalanced order. The control condition was selected to maintain local skin temperatures at approximately the same level throughout the test. Each participant performed the main tests at the same time of day, with a minimum of 24 h between the tests; both tests were performed within 2 weeks. All tests were performed in early winter.

Before each main test, the participants were equipped and dressed in a standard set of commercially available cold-weather protective clothing. The clothing (I_{cl} = 2.7 Clo) was identical in both conditions and consisted of wool socks, thin wool sweater, thin wool pants, an insulated jacket, insulated pants, industrial work shoes, woolen balaclava, and work gloves. The participants were instructed to keep their gloves and balaclava on but could open the zipper on the jacket if they felt too warm.

In order to stabilize the body temperature, the test started with a 20-min resting period at room temperature (approximately 23 °C), with the participants dressed in a thin wool sweater and pants. The participants then donned the rest of the clothing, entered the environmental chamber, and completed a test protocol (Fig. 1) consisting of five test periods (of 10 min each) alternating with four work periods (WPs, of 17 min each). The test started and ended with a test period. The test periods consisted of maximal voluntary contractions (MVC) and seated rest (*see 2.2.1 Test periods*), and the four WPs consisted of three work tasks performed in standing position (*see 2.2.1 Work periods*). The total exposure time in the environmental chamber was 118 min for both temperature conditions.

2.2.1. Test periods

During the 10-min test periods, the participants sat in a customized chair, with both forearms resting on an armrest, at a 90° elbow angle. All periods started with 3-min seated break before performing MVCs. The first test period included right and left wrist extension MVC, right and left wrist flexion MVC, and shoulder abduction MVC tests. These MVCs were used for the normalization of the EMG signal during the WPs. Wrist flexion and shoulder abduction MVC of the right side was measured during test period two to five in order to verify possible fatigue caused by the WPs. The MVCs had a duration of 2–3 s and was performed twice per location, with a 2-s break between the two contractions, and with a 1-min break between locations. For the shoulder abduction MVC, the participants lifted two handles attached to the floor, with a shoulder angle of approximately 80°. The participants then rested for the remaining time.

2.2.2. Work periods

The four WPs all consisted of three dynamic tasks, each of which was performed continuously for 5 min, with a 1-min break between tasks. The first task involved manual overhead work (work high, WH) (at approximately 180 cm above the ground) and the second task involved identical manual work at the hip level (work low, WL) (at approximately 110 cm above the ground). The height of the participants ranged from 172 cm to 192 cm. The manual work consisted of hanging chain links on a hook on the left side, then tying four knots on a climbing rope, and then hanging chain joints on a hook on the right side, before unhinging the chain joints and undoing the knots; all steps were repeated for 5 min. All work included the use of both arms, and the whole body posture was unrestricted to encourage realistic postural selections. To represent shifts in work type and workload, the third dynamic task was manual material handling below the hip level and consisted of lifting a set of 5 kg dumbbells from the floor onto a 50 cm high case and then putting them

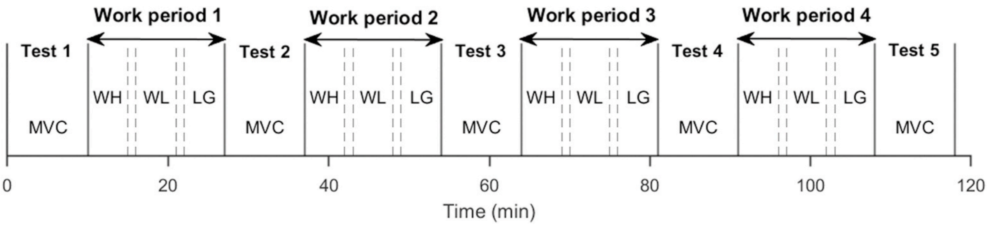

Fig. 1. Schematic of timeline and protocol. LG, lifting exercise from ground level; MVC, maximal voluntary contraction; WH, work high; WL, work low.

down again for 5 min. To represent a realistic work scenario, the participants were instructed to work at a natural pace, and they were repeatedly encouraged to keep the pace equal at all work and temperature configurations. All tests were observed by the test leader.

2.3. Measurements

To evaluate muscle activation level, surface electromyography (EMG) results were obtained throughout each trial from the right and left flexor digitorum superficialis, right and left extensor digitorum, and right middle deltoid. At each site, a dual self-adhesive, disposable, pregelled surface Ag/AgCl electrode (Noraxon dual electrodes Ag/AgCl with an interelectrode distance of 2 cm; Noraxon Inc., Scottsdale, AZ, USA) was attached to the skin in line with the muscle fibers according to the Surface Electromyography for the Non-Invasive Assessment of Muscles (SENIAM) guidelines (Hermens et al., 2000). Before electrode attachment, the skin was shaved if necessary, rubbed with abrasive lotion, and cleansed with an ether/alcohol mixture. The electrodes were positioned at the same place for both tests by marking the skin at the first test. EMG signals were amplified (500 ×), bandpass filtered (20–500 Hz), displayed in real time and digitized at a sampling rate of 1500 Hz, and analyzed using MATLAB® R2019a (MathWorks, Natick, MA, USA). The maximal EMG signal (RMS_{max}) of the muscles was determined as the highest 0.5-s (gliding window) root mean squared (RMS) value of two MVC attempts in the first resting period. The raw signal was divided into seconds for all four WPs. To assess the muscle activation level, the RMS value of each second during the WPs was then normalized by the RMS_{max} of each participant for each condition ($\%RMS_{max}$). Median power frequency (MdPF) was calculated for the middle deltoid muscle (DE) for each second during WH to identify signs of muscle fatigue. Spectral analyses were performed using Welch's power spectral density estimate. A 5-s median filter was used for both $\%RMS_{max}$ and MdPF data for each WP. $\%RMS_{max}$ was averaged from the left and right wrist extensor (extensor digitorum) and flexor (flexor digitorum superficialis) muscles.

Maximal muscle force was measured during right wrist flexion MVC using a force cell (Noraxon DTS Force Sensor; Noraxon Inc., Scottsdale, AZ, USA), which collected data together with the EMG signals at a sampling rate of 1500 Hz. Maximal muscle force during shoulder abduction MVC was measured using a strain gauge sensor (Ergotest Technology AS, Langesund, Norway), with a sampling rate of 100 Hz. Peak force was used for further analyses.

Skin temperatures were measured continuously using 12 skin thermistors (YSI 400; Yellow Springs Instruments, Yellow Springs, OH, USA) positioned on the forehead, right chest, scapulae, stomach, posterior upper arm, anterior forearm, dorsal side of the hand, palmar side of the distal phalanx of the middle finger, anterior thigh, posterior thigh, anterior calf, and posterior calf. Mean skin temperature (T_{sk}) was calculated according to the method used by Teichner (1958).

At the end of every test period, the participants were asked to rate their perceived thermal sensation (PTS) on their whole body and hands using a seven-point questionnaire (ISO, 2005), and their sensation of shivering and sweating on a scale of 1–7 (Ha et al., 1996). They were also asked to rate their thermal comfort on a scale of 1–4 points, where 1 is comfortable, 2 is slightly uncomfortable, 3 is uncomfortable, and 4 is very uncomfortable. After each of the three dynamic tasks in all four WPs, the participants were asked to rate their perceived exertion (RPE) using the 6–20 Borg scale (Borg, 1970). Heart rate (HR) was continuously recorded using an HR monitor (Polar S810™; Polar Electro Oy, Kempele, Finland). The HR values of the final 2 min of each WP were averaged.

2.4. Statistical analysis

For statistical analyses, SPSS® Statistics 25 (IBM Corp., New York, USA) and Stata/MP 15.1 (StataCorp, Texas, USA) programs were used. Two-way repeated-measures analysis of variance was used to examine the main effect of ambient temperature (T_a) and WP and their interaction for $\%RMS_{max}$, HR, RMS_{max}, MVC, and T_{sk}. Owing to technical failures, we lost temperature data from one participant and the HR data from another, both in the cold condition. This reduced the n in these parameters to 13. The assumption of sphericity was assessed using Mauchly's test of sphericity. If required, the Greenhouse–Geisser adjustment was used to adjust the p-value. Normality of residuals was assessed both visually and using the Shapiro–Wilk test. To assess the possible development of fatigue for the DE within the WPs, $\%RMS_{max}$ and MdPF were assessed using a multilevel mixed-effects linear regression model. The model included a random intercept and slope for participants and WPs, and a two-way full factorial analysis for the fixed effects of ambient temperature condition and time. The number of observations was as follows: participants × WPs × ambient temperature ($14 \times 4 \times 2 = 112$). For analysis within each condition, Friedman's test was used for the nonparametric data (RPE, PTS), and Wilcoxon signed ranks test with Bonferroni corrections was used for paired samples between conditions. Nonparametric data are presented as median and range, all other data are presented as mean ± standard deviation (SD), unless otherwise stated, and differences were considered significant when $p < 0.05$.

3. Results

The muscle activation level for the deltoid muscle during WH was approximately 15 $\%RMS_{max}$ and increased slightly over the working periods in both the cold and control conditions ($F(1.3, 17.5) = 5.44$, $p = 0.024$); however, there were no significant differences between the two ambient temperature conditions ($F(1, 13) = 0.64$, $p = 0.439$) or any interaction effect ($F(3, 39) = 1.00$, $p = 0.402$) (Fig. 2). The deltoid muscle activation level during WL was approximately 5% RMS_{max}, one-third of the level during WH. No differences between ambient conditions and changes with WP or interactions were found for the deltoid muscle during WL (effect T_a: $F(1, 13) = 0.92$, $p = 0.356$; WP: $F(1.9, 24.7) = 0.41$, $p = 0.655$; $T_a \times$ WP: $F(1.9, 25.1) = 0.32$, $p = 0.720$). Muscle activation level in the wrist flexors and extensors during WH were initially approximately 8 $\%RMS_{max}$ and 20 $\%RMS_{max}$, respectively, and were slightly increased in the cold and decreased in the control condition over the working periods (effect T_a: $F(1, 13) = 2.78$, $p = 0.155$; WP: $F(3, 39) = 1.28$, $p = 0.295$; $T_a \times$ WP: $F(2.2, 28.9) = 5.88$, $p = 0.006$ for wrist flexors, and effect T_a: $F(1, 13) = 2.66$, $p = 0.614$; WP: $F(3, 39) = 2.30$, $p = 0.042$; $T_a \times$ WP: $F(3, 39) = 8.41$, $p < 0.001$ for wrist extensors) (Fig. 2). During WL, the muscle activation of the wrist muscles was

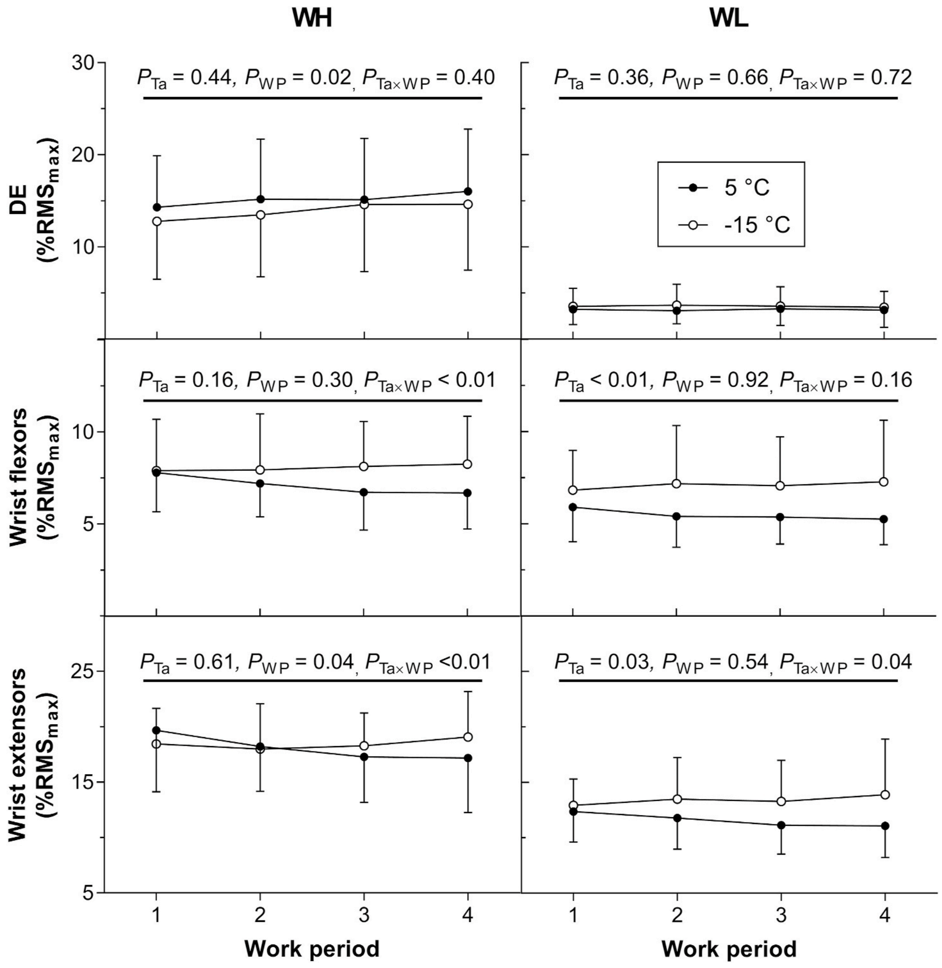

Fig. 2. Mean (±SD) muscle activation level (%RMS$_{max}$) for the middle deltoid muscle (DE), wrist flexors, and wrist extensors during overhead work (WH) and work at the hip level (WL) during the four work periods in control (5 °C) and cold (−15 °C) conditions. Ta, ambient temperature; WP, work period; Ta × WP, ambient temperature × work period interaction. $n = 14$.

approximately 7% RMS$_{max}$ and 13% RMS$_{max}$ for the flexors and extensors, respectively, somewhat lower than those during WH. In general, there was a higher muscle activation level in the wrist flexors and extensors in the cold condition during WL (effect T$_a$: $F(1, 13) = 13.03, p = 0.003$; WP: $F(3, 39) = 0.160, p = 0.923$; T$_a$ × WP: $F(1.6, 21.2) = 2.09, p = 0.155$ for wrist flexors, and effect T$_a$: $F(1, 13) = 6.18, p = 0.27$; WP: $F(1.8, 24.0) = 0.62, p = 0.536$; T$_a$ × WP: $F(1.7, 22.6) = 4.09, p = 0.035$ for wrist extensors). For the wrist extensors, the increase in %RMS$_{max}$ over the working periods was different between conditions, resulting in larger differences during the last working period.

The two ambient temperature conditions in our experiments had no effect on wrist flexion MVC, shoulder abduction MVC, and concurrent RMS$_{max}$ of the middle deltoid muscle (DE) and flexor digitorum superficialis (FDS); these variables did not change over time (Table 1).

T$_{sk}$ decreased more in the cold condition than in the control condition and was 2.2 ± 1.1 °C lower in the cold compared to the control condition at the last WP (effect T$_a$: $F(1, 12) = 47.11, p < 0.001$; WP: $F(1.5, 18.2) = 49.9, p < 0.001$; T$_a$ × WP: $F(2.4, 28.7) = 21.9, p < 0.001$)

Table 1
Results for the maximal voluntary contractions (MVC) of shoulder abduction (SA) and wrist flexion (WF) during the five test periods and the corresponding muscle activation (RMS$_{max}$) of the middle deltoid muscle (DE) and flexor digitorum superficialis (FDS) across ambient temperature conditions.

	5 °C					−15 °C				
	Test 1	Test 2	Test 3	Test 4	End	Test 1	Test 2	Test 3	Test 4	End
SA, DE										
MVC (N)	71 ± 15	70 ± 14	70 ± 13	73 ± 14	74 ± 12	73 ± 14	70 ± 12	71 ± 15	73 ± 13	74 ± 13
RMS$_{max}$ (μV)	512 ± 190	493 ± 179	480 ± 156	510 ± 169	522 ± 211	534 ± 216	500 ± 153	526 ± 222	539 ± 251	524 ± 206
WF, FDS										
MVC (N)	280 ± 57	284 ± 58	280 ± 57	283 ± 51	280 ± 63	285 ± 53	302 ± 49	294 ± 48	297 ± 42	289 ± 47
RMS$_{max}$ (μV)	802 ± 231	795 ± 272	739 ± 280	735 ± 284	744 ± 270	811 ± 227	805 ± 267	780 ± 206	800 ± 254	850 ± 306

RMS$_{max}$, maximal RMS value of the MVC.
No significant differences of main or interaction effects.
Data are presented as mean (±SD). $n = 14$.

MdPF for the DE was 2.7 Hz (95% confidence interval [CI] 2.3, 3.1, $p < 0.001$) lower in the cold condition, and it decreased during WH in both ambient conditions, with a 0.7 Hz min^{-1} (95% CI 0.5, 0.8, $p < 0.001$) slower decrease in the cold condition (Fig. 3). Muscle activity level in the DE was 1.3 %RMS$_{max}$ (95% CI 1.0, 1.6, $p < 0.001$) lower in the cold condition, and it increased by 0.7 %RMS$_{max}$·min^{-1} (95% CI 0.3, 1.2, $p < 0.001$) in both ambient conditions.

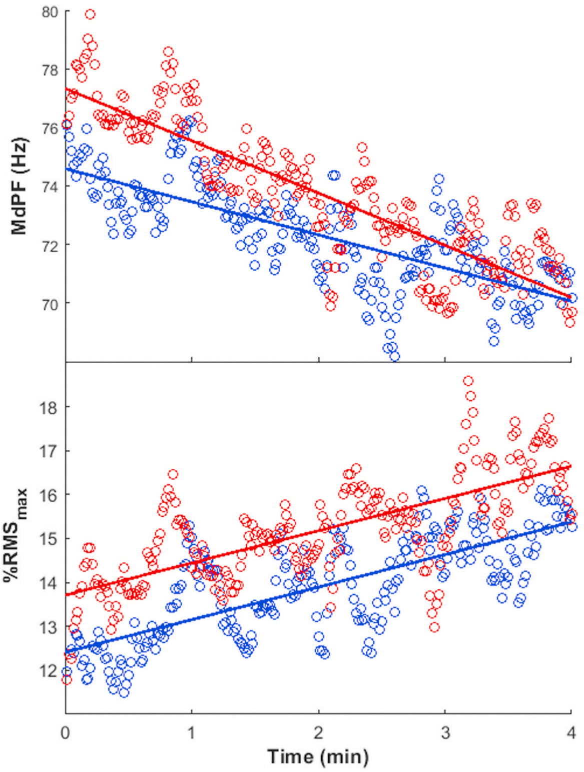

Fig. 3. Median power frequency (MdPF) and muscle activation level (%RMS$_{max}$) for the middle deltoid muscle (DE) as a mean of the four work periods during the overhead work (WH) in control (5 °C, red) and cold (−15 °C, blue) ambient conditions. One circle per second, representing the mean of four WPs and all participants. MdPF: significant main effect of ambient temperature condition, time, and interaction (ambient temperature × time). %RMS$_{max}$: significant main effect of ambient temperature condition and time. $n = 14$. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

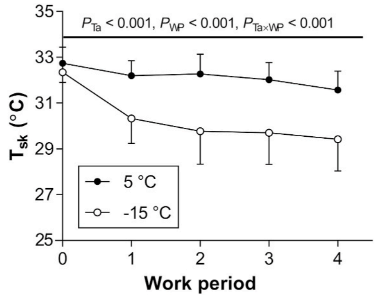

Fig. 4. Mean (±SD) of mean skin temperature (T_{sk}) in control (5 °C) and cold (−15 °C) conditions. There was a significant main effect of ambient temperature (T_a), main effect of work period (WP) and of interaction between ambient temperature and work period (T_a × WP). $n = 13$.

(Fig. 4). Local skin temperatures at the scapula, posterior upper arm, anterior forearm, hand, and middle finger were 0.8 ± 1.3 °C, 3.3 ± 1.8 °C, 1.6 ± 2.6 °C, 7.3 ± 3.6 °C, and 15.2 ± 5.6 °C lower in the cold condition than in the control condition at the last WP, respectively ($n = 13$). In the cold condition, participants felt that the hands became increasingly colder with exposure time ($p = 0.008$), while they reported that they felt slightly warm at the hands throughout the control condition (Table 2). The body was rated as neutral in the cold condition and significantly warmer ($p < 0.01$) as slightly warm in the control condition, and some sweating was reported in the control condition ($p < 0.001$). Correspondingly, the participants felt slightly less comfortable in the control condition ($p = 0.015$) (Table 2).

HR was higher in the control condition during WH (effect T_a: F (1, 12) = 4.80, $p = 0.049$; WP: F(1.5, 18.6) = 0.37, $p = 0.644$; T_a × WP: F (1.6, 19.7) = 1.02, $p = 0.366$), and no other differences in HR were observed (Table 3). There were no differences in RPE, and the participants generally found WH to be somewhat hard and WL to be extremely light to very light (Table 3).

4. Discussion

The main aim of this study was to evaluate the effect of working position and cold environment on muscle activation level and fatigue in the upper limb during manual work tasks.

This study demonstrated that the muscle activation level in the forearm was higher during work in the cold condition (−15 °C) than in the control condition (5 °C), for both work positions (WH and WL) (see Fig. 2). For the DE, the muscle demand was approximately three times as high as that during WH, but there was no additional cost of working in the cold. Moreover, signs of muscle fatigue were observed in the EMG signal of the DE during the WH periods both in the cold and control conditions, but no loss of force-generating capacity as a sign of overall muscle fatigue was measured in either condition.

Our finding of higher muscle demand in the forearm in the cold condition is in line with previous studies that observed greater EMG activity during dynamic work in cold environments than in warmer environments, both with (Oksa et al., 2002) and without cold-weather protective clothing (Piedrahita et al., 2008; Sormunen et al., 2009). Increased muscle activation and decreased muscle performance due to reduced muscle temperature have previously been demonstrated (Oksa et al., 1997). Oksa et al. (2002) demonstrated that systemic cooling of the body or local cooling of the forearm in an ambient temperature of 5 °C both led to lower skin temperatures, lower muscle temperatures, increased muscle activation, increased level of coactivation of the agonist–antagonist pairs, and increased fatigue in the forearm muscle in comparison with thermoneutral conditions. In our study, the decrease in local skin temperature was less owing to the protective clothing, but there still was a reduction in the skin temperature, especially in the distal parts of the upper limb. This might also reflect a subsequent decrease in muscle temperature, leading to the higher muscle activation level across WPs in the cold environment in the forearm muscles but not in the DE. However, because we measured skin temperature, above the muscles, and not the muscle temperature, this remains uncertain. Other factors such as reduced manual dexterity due to cold fingers and hands may also explain the observed higher muscle activation level in the forearm.

The skin temperature was approximately 2 °C lower on the anterior forearm and approximately 15 °C lower on the middle finger in the cold condition than in the control condition. Finger skin temperature decreased rather rapidly during the cold condition, and after only 10 min of exposure to −15 °C, it decreased to below 20 °C. At finger skin temperatures below 20 °C, manual dexterity begins to decline (Heus et al., 1995; Ray et al., 2019). The decline in manual dexterity at low hand and finger skin temperatures is due to several factors. Lowered tissue temperatures can decrease the neural conduction velocity (De Jesus et al., 1973) and increase viscosity of the synovial fluid and the tissues of the hand (Hunter et al., 1952) which may make movements in the cold harder and thus requiring more muscle power. Consequently, lower hand and finger temperatures may have influenced muscle activation in the forearm in our study, because the muscles involved in moving the fingers and thumb are located both in the hand and forearm.

In contrast to the higher muscle activation level measured in the forearm, no adverse effect of cold on muscle function was found for the DE (se Figs. 2 and 3). In general, we measured a lower %RMS$_{max}$ and MdPF for the DE during WH in the cold condition. The DE during WH worked in a relatively static posture, while the movements of the hands and fingers were dynamic. Our findings are in line with the concept that

Table 2
Perceptual responses at the test periods across ambient temperature conditions.

	5°C				−15°C			
	Test 1	Test 2	Test 3	Test 4	Test 1	Test 2	Test 3	Test 4
PTS[a]: body	1 [0, 2]	1 [0, 3]	1 [0, 3]	1.5 [0, 3]	0 [−1, 0]*	0 [−1, 0]*	0 [−1, 0]*	0 [−2, 1]*
PTS[a]: hands	1 [0, 2]	1 [−1,3]	1 [0, 3]	1 [0, 3]	**0 [−2, 1]** *	**−2 [−3, 0]** *	**−1 [−2, 1]** *	**−1 [−2, 3]** *
Thermal comfort[b]	**1 [1, 2]**	**1 [1, 2]**	**1 [1, 3]**	**1 [1, 3]**	1 [1, 2]	1 [1, 2]	1 [1, 2]	1 [1, 2]
Shivering/sweating sensation[c]	**4 [4, 5]**	**4.5 [4, 6]**	**5 [4, 6]**	**5 [4, 6]**	4 [4, 4]	4 [4, 4]*	4 [3, 4]*	4 [3, 5]*

PTS, perceived thermal sensation.
Data are presented as the median and range [min, max]. $n = 14$.
Significant change over the test periods ($p < 0.05$) within each ambient temperature condition (Friedman's test) is indicated using bold font.
* Significantly different ($p < 0.05$) from paired sample (Wilcoxon signed ranks test) at 5°C.
[a] 3, hot; 2, warm; 1, slightly warm; 0, neutral; −1, slightly cool; −2, cool; −3, cold.
[b] 1, comfortable; 2, slightly uncomfortable; 3, uncomfortable; 4, very uncomfortable.
[c] 1, vigorously shivering; 2, moderately shivering; 3, slightly shivering; 4, neither shivering nor sweating; 5, some sweating; 6, moderate sweating; 7, heavy sweating.

Table 3
Heart rate (HR) and rate of perceived exertion (RPE) data in the work periods (WPs) across ambient temperature conditions.

Work mode		5 °C				−15 °C			
WP 1			WP 2	WP 3	WP 4	WP 1	WP 2	WP 3	WP 4
HR (beats·min^{-1})[a]	WH	95 ± 13	96 ± 13	97 ± 13	96 ± 13	90 ± 13	91 ± 13	91 ± 15	92 ± 15
HR (beats·min^{-1})	WL	82 ± 12	85 ± 13	85 ± 12	85 ± 12	80 ± 13	80 ± 12	82 ± 14	82 ± 15
RPE	WH	14 [12, 17]	14 [10, 18]	13.5 [10, 18]	14 [10, 18]	13 [9, 17]	13.5 [10, 18]	14 [10, 19]	14.5 [10, 18]
RPE	WL	8 [6, 13]	8 [6, 13]	8.5 [6, 13]	8.5 [6, 14]	7.5 [6, 11]	9 [6, 11]	8.5 [6, 13]	8.5 [6, 13]

WH, overhead work; WL, work at the hip level.
HR ($n = 13$) data are presented as mean (±SD) and RPE ($n = 14$) data are presented as the median [min, max].
[a] Indicates significant main effect of ambient temperature ($P_{\text{Ta}} = 0.049$).

isometric exercise is less temperature dependent than dynamic exercise (Bergh and Ekblom, 1979; Oksa, 2002; Wakabayashi et al., 2015). Submaximal isometric endurance has been found to improve with reduced muscle temperature, with optimal performance for muscle temperatures at 27–28 °C (Clarke et al., 1958; Petrofsky and Lind, 1975). This increase in time to fatigue is likely a result of an increase in relaxation time of the contraction coupling mechanism (i.e., prolonged contraction) (Davies et al., 1982), which decreases the firing frequency of the muscle (Segal et al., 1986) and thereby reduces the energy cost of force maintenance (Drinkwater, 2008).

The use of protective clothing, including gloves, is necessary for work in cold climates to reduce heat loss. Because the clothing itself is known to increase the metabolic cost to the wearer (Dorman and Havenith, 2009; Teitlebaum and Goldman, 1972), as well as increase the muscle activation level (Renberg et al., 2020), the participants in our study wore the same garments at both temperature conditions. The clothing reduced heat loss to the environment and was enough to keep the participants thermally comfortable in −15 °C for 2 h. Nevertheless, the extremities were prone to cooling, which may explain the higher muscle demand in the wrist muscles. In addition, it is possible that the fabric of the gloves became stiffer when it was cold, making manual tasks more difficult and requiring more power to perform the work tasks. Our results also demonstrate that if thermal comfort is to be maintained and sweating in the clothes is to be avoided when performing physical work in the cold, the extremities will often be somewhat cooled (see Table 3).

No differences in fatigue, measured as isometric MVC force, were found within or between conditions (see Table 1). MVC force is regarded as a reliable and valid measurement of muscle fatigue (Vøllestad, 1997). Similar findings were reported by Wiggen et al. (2011), who found no significant differences in grip strength at ambient temperatures ranging from 5 °C to −25 °C, while performing manual dexterity tasks and wearing cold-weather protective clothing. Thornley et al. (2003) found that local tissue temperature did not change peak force production during isometric knee extension. Others have found a decrease in the MVC force in cold conditions compared with thermoneutral conditions during repetitive work performed almost without breaks for 2 h at 10% MVC (Oksa et al., 2002); however, this response is reduced by intermittently increasing the workload to 30% MVC (Oksa et al., 2006). The work performed by the participants in our study was varied and they had breaks between the WPs; thus, it is reasonable that there were no signs of overall muscle fatigue.

RPE, HR, and $\%\text{RMS}_{\max}$ for the DE indicated that WH is more strenuous than WL, but there is no added effect of working in the cold (see Table 3 and Fig. 2). We also found a reduction in the MdPF and an increase in $\%\text{RMS}_{\max}$ for the DE during the 5-min WH periods under both conditions (See Fig. 3), which is consistent with the development of muscle fatigue. However, no loss of force-generating capacity as a sign of overall muscle fatigue was measured for shoulder abduction in either condition (see Table 1). This demonstrates that enough recovery time was supplied and that the complete 2-h protocol with intermittent WPs and breaks was not fatiguing for the participants. However, the participants in this study were all young, healthy, trained men, and a selection more representative of a workforce could have found the protocol more fatiguing.

Some limitations of this study should be considered when interpreting these results. The effect of work in the cold is studied independent of an increase in thermal insulation, ensuring that a possible effect on the EMG measures is because of changes in body temperature and not an effect of the extra added layers of clothing and weight of the protective clothing. However, in a real-life work setting, one can assume that a higher level of total insulation would be worn in −15 °C than 5 °C, possibly increasing the muscle demand during work tasks due to added layers and weight of clothing. Furthermore, EMG measures obtained under nonisometric and nonisotonic contractions can be affected by variability in muscle force, length, and velocity. However, the cyclic nature of the tasks and the use of averaging over the tasks in the four WPs should make the EMG data derived from the dynamic work representative of the underlying muscle activation. In addition, it has been suggested that when monitoring and quantifying shoulder muscle fatigue during overhead dynamic tasks standard EMG analysis can be used (Nussbaum, 2001). Finally, allowing the participants to work at a self-selected pace and with an unrestricted whole body posture increases variability. For example, it leads to the possibility of changing the work posture as the muscles fatigue, and there might have been changed load sharing between multiple muscle synergists, which was not measured in this study. Also, the work pace might be unintentionally changed either to regulate metabolic heat production as a response to the ambient temperature, or to maintain the same perceived exertion due to ambient temperature or type of work. Nevertheless, because maintenance of a strict pacing and body posture is uncommon in industrial settings, the findings of this study can be relevant to applied scenarios. Further research is needed to investigate whether work pace, postural selections or load sharing during dynamic work are changed in cold conditions.

5. Conclusions

In conclusion, muscle activation level in shoulder during WH was three times higher compared to WL, but no additional activation was observed in the cold condition. The DE showed signs of developing fatigue during dynamic WH, but no adverse effect was measured in the cold condition compared with the control condition. Wearing cold-weather personal protective clothing in −15 °C maintained the individual's thermal comfort, but the mean skin and local skin temperatures decreased, especially in the extremities. Muscle activation level in the forearm increased during dynamic manual work in the cold condition, for both WH and WL, increasing the physical strain on the worker.

CRediT authorship contribution statement

Julie Renberg: Formal analysis, Writing - original draft, Visualization. **Øystein Nordrum Wiggen:** Conceptualization, Methodology, Investigation, Writing - review & editing. **Per Øyvind Stranna Tvetene:** Investigation, Writing - review & editing. **Hilde Færevik:** Funding acquisition, Conceptualization, Writing - review & editing. **Mireille Van Beekvelt:** Conceptualization, Methodology, Writing - review & editing. **Karin Roeleveld:** Conceptualization, Methodology, Supervision, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ergon.2020.103035.

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