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The effect of mild whole-body cold stress on isometric force control during hand grip and key pinch tasks

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ABSTRACT

Prolonged exposure to cold can impair manual performance, which in turn can affect work task performance. We investigated whether mild whole-body cold stress would affect isometric force control during submaximal hand grip and key pinch tasks. Twelve male participants performed isometric hand grip and key pinch tasks at 10% and 30% of maximal voluntary contraction (MVC) for 30 and 10 s respectively, in cold (8 °C) and control (25 °C) conditions. Finger temperature decreased significantly by 18.7 ± 2.1 °C and continuous low-intensity shivering in the upper trunk increased significantly in intensity and duration during cold exposure. Rectal temperature decreased similarly for the 8 °C and 25 °C exposures. Force variability (FCv) was <2% for the hand grip tasks, and <3% for the key pinch tasks. No significant changes in FCv or force accuracy were found between the ambient temperatures. In conclusion, isometric force control during hand grip and key pinch tasks was maintained when participants experienced mild whole-body cold stress compared with when they were thermally comfortable.

1. Introduction

Manual performance is crucial for both daily activities and for performing work tasks. Motor function and manual dexterity are factors that affect manual performance. In cold environments, clothing is worn to protect against heat loss, but it is still common to experience peripheral cooling. Cooling of muscle and tissue can impair both muscular performance during dynamic exercises (Oksa, 2002; Racinais and Oksa, 2010) and manual dexterity (Heus et al., 1995). Cold exposure can cause decreases in manual and finger dexterity, starting below finger skin temperatures of 12–20 °C (Ray et al., 2019).

The ability to maintain a steady force output during isometric tasks represents another aspect of motor function. While the effect of cold stress on finger and manual dexterity have been investigated extensively, there have been fewer studies on the effects of cold on isometric force control. The effects of temperature on maximal grip strength have been investigated more extensively, but these showed ambiguous results. Some found no change in maximal grip strength (Flouris et al., 2006; Imamura et al., 1998; Immink et al., 2012; Wiggen et al., 2011; Zander and Morrison, 2008), while others found a reduced maximal grip strength in the cold (Bowen, 1968; Chi et al., 2012; O'Connor et al., 2009; Vincent and Tipton, 1988). Identifying the cause of the differences in these results is difficult because of large differences in cooling methods, cooling rates, level of body cooling, and task protocols. Although maximal grip strength can be important for some specific tasks, submaximal forces are more widely used, and—for example—are required for the effective use of hand tools and instruments. Thus, submaximal force control might be more relevant for work performance. To our knowledge, only two studies have investigated the effects of whole-body cooling on submaximal isometric force control in the upper

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Abbreviations: EMG, electromyography; FCv, force variability; MR, metabolic rate; MVC, maximal voluntary contraction; MFP, mean force percentage; PTS, perceived thermal sensation; RER, respiratory exchange ratio; RMS, root-mean-square; RMSE, root-mean-square error; T_{finger}, finger skin temperature; T_{hand}, hand skin temperature; T_{re}, rectal temperature; T_{sk}, mean skin temperature; VO_2, oxygen consumption.

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limb. One study included a 15-sec hand grip exercise at 10% of maximal voluntary contraction (MVC) (Meigal et al., 1998). They found that hand grip force control was not affected by exposure to cold air (10 °C) or by the combination of cold air (10 °C) and visible shivering (induced by drinking 1 L of cold water). The other study investigated the effect of ambient temperature on climbing-specific finger flexor performance, and no effect of ambient temperature on force control during an intermittent fatiguing task at 40% MVC was found (Phillips et al., 2017). Similarly, during local cooling no consistent effect of temperature has been found on force variation during submaximal MVCs for index finger abduction (Geurts et al., 2004) or wrist flexion (Mallette et al., 2018, 2019). In addition, a study investigated the effect of hand cooling on pinch grip force modulation, and the results showed that the temporal coordination of fingertip forces during object manipulation was not altered, despite an increase in finger grip force, and impairments in manual dexterity and tactile sensitivity (Cheung et al., 2008).

Exposure to cold can also impair the control of voluntary movement by triggering the shivering response. Shivering activates the same motor units as voluntary movements and can be divided into continuous low-intensity shivering, or thermoregulatory muscle tone, and high-intensity bursts of shivering (Haman et al., 2004; Israel and Pozos, 1989; Meigal, 2002). Continuous low-intensity shivering is a cold-induced increase in muscle tone that does not cause visible bursts of shivering. Continuous low-intensity shivering usually occurs before high-intensity shivering, and is associated with the recruitment of type I muscle fibers, which are also activated during submaximal isometric contractions (Meigal, 2002). The peripheral muscles typically only show continuous low-intensity shivering, while the centrally located muscles are more active during bursts of shivering and contribute the most to sustaining heat production in the cold (Bell et al., 1992; Haman and Blondin, 2017; Tikuisis et al., 1991). Meigal et al. (1998) demonstrated that fine force control during 10% MVC hand grip and elbow flexion tasks was not affected by shivering, while performance accuracy was affected by shivering during shoulder flexion. This demonstrated an effect of bursts of shivering but not of continuous low-intensity shivering on fine force control.

Previous work has demonstrated that isometric force control during a hand grip task is maintained at 10% MVC for 15 s during cold stress (Meigal et al., 1998). The literature does not report whether whole-body cold stress affects the ability to maintain isometric force control during hand grip at 10% MVC for longer than 15 s, or whether cold stress affects isometric force control during hand grip at intensities greater than 10% MVC (Meigal, 2002). In addition, the effect of whole-body cold stress on isometric force control during key pinch tasks, to our knowledge, is lacking. Therefore, the aim of this study was to investigate whether mild whole-body cold stress (defined here by a decrease in mean skin temperature but not in rectal temperature, and with no bursts of shivering) would affect isometric force control during nonfatiguing submaximal hand grip and key pinch tasks at 10% MVC and 30% MVC for 30 and 10 s, respectively.

2. Material and methods

2.1. Participants

Twelve healthy male participants volunteered to participate in this study. Their mean age was 23.8 ± 2.0 years, body mass 75.3 ± 6.5 kg, height 180.3 ± 6.4 cm, and body fat 12.2 ± 3.3%. All participants were right-handed. 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 gave their informed, written consent. The study was approved by the Regional Committee for Medical and Health Research Ethics, North Norway.

2.2. Experimental design

Isometric force tasks for hand grip and key pinch tasks (Fig. 1) were performed at 8 °C (cold condition) and at 25 °C (control condition), with a 30 ± 3% relative humidity at both temperature conditions. These ambient temperatures were chosen based on several pilot studies, where the aim was to cause mild cold stress in the cold condition and to maintain thermal balance in the control condition, when wearing the selected clothing (see below).

The participants visited the laboratory on three occasions, once for a pre-test session and twice for main tests at the cold and control conditions. The purpose of the pre-test session was to inform the participants about the test procedure and to determine the force at isometric MVC for hand grip and key pinch tasks. Then, 30% MVC and 10% MVC values were calculated for each subject. The isometric force tests at these points were then practiced for both hand grip and key pinch tasks at room temperature. All force tasks were performed with the preferred (right) hand. Since body size and composition can influence the rate of heat loss, shivering onset and increase in metabolic rate (Bell et al., 1992; Tikuisis et al., 1991), anthropometric measurements were also measured at the pre-test session. The body height and weight were measured, and skin-folds were measured with a Harpenden skin-fold calliper (John Bull British Indicators ltd., UK) at four different sites: over the biceps brachii muscle, over the triceps brachii muscle, the subscapular skinfold, and the supra-iliac skinfold. The proportion of body fat was calculated using the sum of these four skinfold measurements in line with common directions (Durnin and Womersley, 1974).

Before each main test, the participants wore their personal socs and briefs and were then equipped and dressed in wool mesh shirts (Wool Thermo, Brynje, Norway) and wool mesh pants (Wool Thermo, Brynje, Norway). Calculated basic clothing thermal insulation of the clothing ensemble was 0.53 Clo (ISO, 2008). Fig. 2 provides a timeline of the protocol for the two main tests. Each participant performed a series of MVC exercises for each muscle being recorded by surface electromyography (EMG) for normalization of the shivering measures (see 2.3. Measurements). They also performed two MVCs for hand grip and for key pinch. Each MVC had a duration of 3 s and was performed twice with a 10 s break between contractions, with a 1 min break between different sites. The participants were verbally encouraged during each MVC, and for the hand grip and key pinch MVCs they had visual feedback. Following the MVCs they rested seated at room temperature (23.4 ± 0.7 °C) for 20 min (baseline). Then, each participant entered the environmental chamber and was seated in a chair in front of the table where the grip force and pinch force measurements were performed. The total time in the environmental chamber was 78 min, and consisted of three sets of force measurements, assessment of thermal sensations, and rest periods (Fig. 2). During the force measurements, participants were instructed to rest their forearm on the table with the elbow flexed to approximately 90°.

Each complete set of isometric force tests lasted 10 min. These included isometric hand grip and isometric key pinch tasks at two different intensities: maintaining 30% MVC for 10 s and 10% MVC for 30 s, each performed twice. The order within all the force tests was hand grip tasks before key pinch tasks and all tasks started with the 30% MVCs. Between the two equal intensities there was a 30 s break, between different intensities there was a 1 min break, and between different tasks there was a 2 min break. The participants were instructed to generate the target force rapidly and then to maintain it as accurately as possible with the aid of a digital screen showing the level of force being developed in real time.

After each of the three isometric force tests, the participants were asked to rate their thermal comfort, sensation of shivering and sweating, and perceived thermal sensation (PTS). They were then asked to rest for 10 min while sitting comfortably in the chair with hands resting on their thighs, listening to a podcast. Participants were encouraged to minimize voluntary muscle activity during the resting periods. After the final

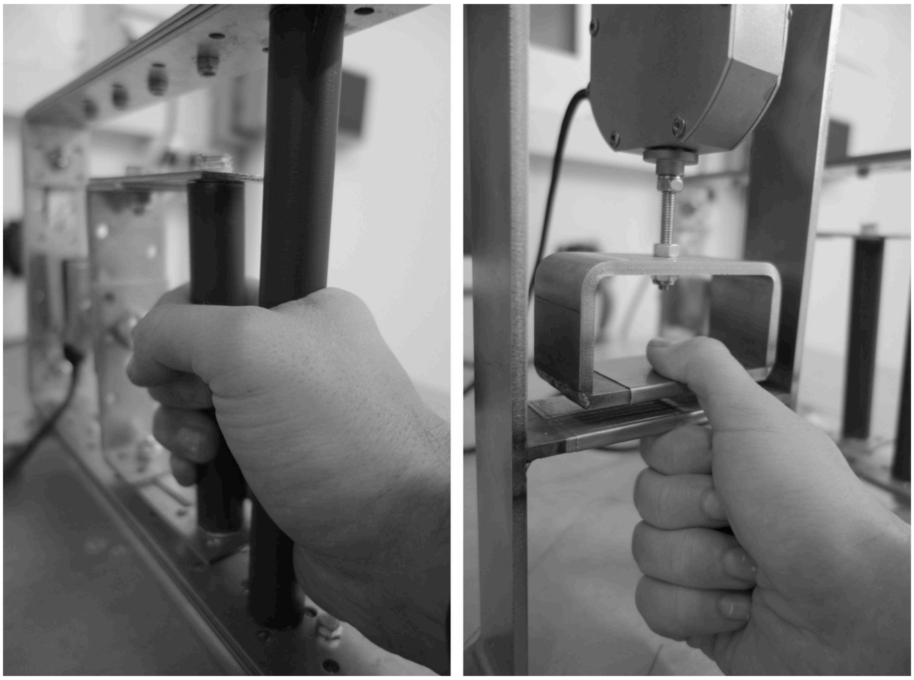

Fig. 1. Illustration of hand grip (left) and key pinch (right) tasks.

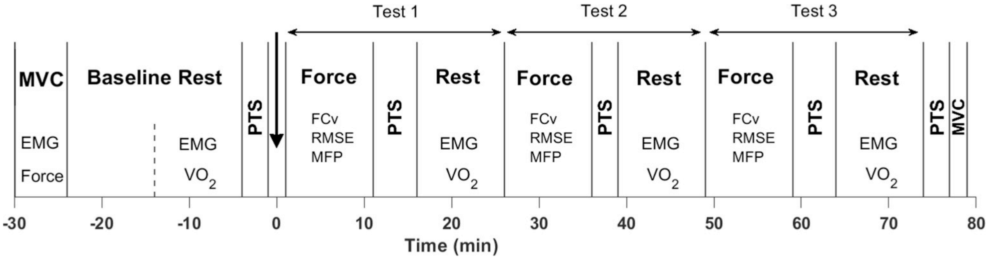

Fig. 2. Schematic of timeline and protocol. The vertical arrow indicates the time of entering the environmental chamber. MVC; maximal voluntary contraction, PTS; perceived thermal sensation (shivering/sweating sensation and thermal comfort were logged at the same time interval), EMG; electromyography, VO_2; oxygen consumption, FCv; coefficient of force variation, RMSE; root-mean-square error, MFP; mean force percentage.

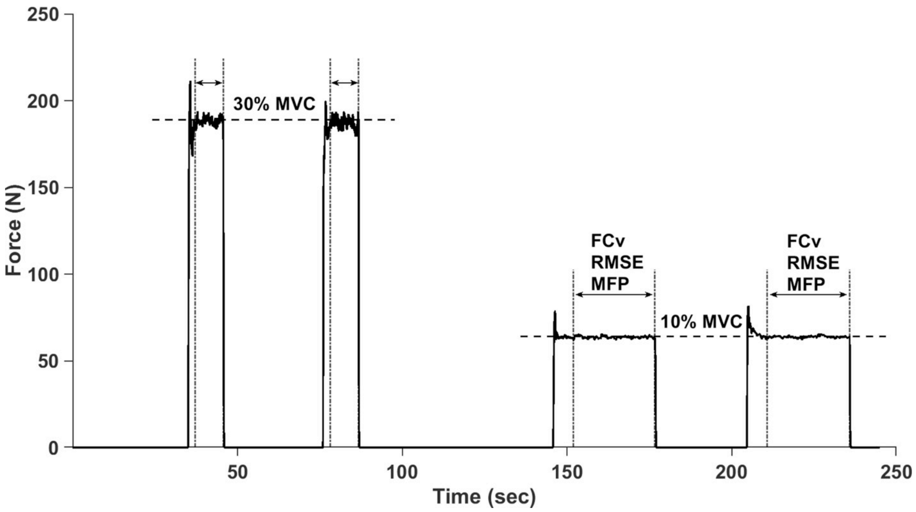

Fig. 3. A typical example of force output, showing the hand grip task for one participant during one of three trials at the control condition. Dashed horizontal lines show the target force for 30% and 10% MVC. Dashed vertical lines and horizontal arrows indicate the range used for calculations of coefficient of force variation (FCv), force error (RMSE) and mean force percentage (MFP).

resting period, they performed two MVC exercises for hand grip and two for key pinch to verify possible fatigue caused by the exercises.

To avoid order effects, the order of the ambient temperature was balanced across participants. The two main tests for each participant were performed during November or December, at the same time of day, within 7 days. The participants were instructed to avoid alcohol for 24 h before testing and avoid consuming coffee, tea, or chocolate for 2 h before testing.

2.3. Measurements

Force production was measured with customized hand grip and key pinch dynamometers using strain gauges (333A; Ktoyo, S. Korea and VZ101AH; Vetek Weighing AB, Sweden, respectively) at a frequency of 100 Hz. The data were digitized and stored using Muscle Lab V8 (Ergotest Technology A.S., Norway), and analyzed using MATLAB® R2018a (MathWorks, Natick, MA, USA). To remove the time used to reach the target force, the last 80% of each force signal was used in calculations (see Fig. 3). The coefficient of force variation (FCv, standard deviation, SD, divided by the mean, as a percentage) was calculated to measure the relative variability of the force maintained during each task. The force signal with the lowest FCv of the two repetitions within each test and each intensity was used for further analysis of FCv, mean force percentage (MFP) and force accuracy. MFP (mean force divided by MVC force, as a percentage) was calculated to measure the actual force level maintained by the participants. Root-mean-square error (RMSE) of the target force was used as a measure of accuracy, where the closer the values are to zero the higher the accuracy. For the two MVCs performed at the start and end of the trials, that with the highest value was used.

Rectal temperature (T_{re}) was measured continuously at 10-cm depth using a thermistor probe (YSI 400; Yellow Springs Instruments, USA). Skin temperature was measured continuously using 13 YSI 400 skin thermistors positioned on the forehead, neck, chest, upper back, abdomen, upper arm, forearm, hand, finger, anterior thigh, posterior thigh, anterior calf, and posterior calf. Skin thermistors positioned on the upper limb were placed on the left side to ensure that they did not affect the force control tasks. To calculate the mean skin temperature (T_{sk}), weighted skin temperatures from the forehead, upper back, chest, upper arm, forearm, hand, anterior thigh, and anterior calf were used (Gagge and Nishi, 1977).

To calculate heat production during the resting periods gas-exchange variables (Oxycon Pro; Jaeger GmbH, Germany) were recorded continuously during the resting periods using the “mixing chamber” approach. Oxygen consumption (VO_2) and the respiratory exchange ratio (RER) in the final 5 min of each resting period were averaged and used for calculations of metabolic rate (MR) (Weir, 1949) (Equation (1)), and converted to watts (Equation (2)).

$$MR\left(Kcal\cdot min^{-1}\right)=((1.1\cdot RER)+3.9)\cdot VO_2 \tag{1}$$

$$MR(watt)=\frac{(MR(Kcal\cdot min^{-1})\cdot\ 4200)}{60} \tag{2}$$

After every resting period, the participants were asked to rate their 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 whether they felt thermally comfortable, rated on a 1–4 scale (Gagge et al., 1967).

Surface EMG was used to evaluate shivering activity in the upper body during the resting periods in the cold condition (Mobi 6; TMSi, Netherlands). EMG signals were recorded on the latissimus dorsi and pectoralis major muscles as they are upper trunk muscles known to contribute significantly to shivering during cold exposure (Bell et al., 1992; Haman et al., 2004; Meigal et al., 1998, 2003), and on the biceps brachii, triceps brachii, and middle deltoid muscles as representative of the upper limb. At each site, two self-adhesive, disposable, pre-gelled surface Ag/AgCl electrodes (Ambu Neuroline 720 00-S; Ambu, Denmark), with an electrode distance of 2 cm, were attached to the skin 4 cm medial to the axillary fold for the pectoralis major, 3 cm caudal and lateral to the angulus inferior for the latissimus dorsi, on the line from the acromion to the lateral epicondyle of the elbow on the greatest bulge of the muscle for the middle deltoid, on the line between the medial acromion and the fossa cubit at 1/3 from the fossa cubit for the biceps bracii, and at 50% on the line between the posterior crista of the acromion and the olecranon at 2 finger widths medial to the line for the triceps brachii. Adjustments to these electrode placements were made to ensure placement on the muscle belly and orientation parallel to muscle fibres 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, rubbed with an abrasive lotion, and cleansed with an ether/alcohol mixture.

Raw EMG signals were collected at 2048 Hz and band-pass filtered at 20–500 Hz, using MATLAB R2018a. Participants were encouraged to minimize voluntary muscle activity during the resting periods (in both ambient temperatures). Shivering intensity, shivering time, and number of shivering bursts were calculated using the methods described by Haman et al. (2004). First, amplitude values were calculated by root-mean-square (RMS) from raw EMG signals using a 50-ms overlapping window (50%). For each muscle, the baseline RMS ($RMS_{baseline}$) was determined as the mean of the last 10 min of the baseline resting period before entering the climate chamber. Shivering RMS (RMS_{shiv}) was determined during the three quiet sitting periods in the climate chamber, and maximal RMS (RMS_{mvc}) was determined from the MVCs prior to the baseline resting period. Shivering intensity was then calculated using the following equation (Equation (3)).

$$Shivering\ \ intensity\ \ (\%MVC)=\frac{RMS_{shiv}\ \ -\ \ RMS_{baseline}}{RMS_{mvc}\ \ -\ \ RMS_{baseline}}\times 100 \tag{3}$$

Shivering time was calculated as the amount of time for which the shivering intensity was above $RMS_{baseline}$ during each resting period as a percentage of the resting period time. The numbers of shivering bursts were calculated by identifying EMG intervals with a duration of >0.2 s, an interburst interval >0.75 s, and an amplitude higher than the intensity threshold at each recording period. For this, the intensity threshold was determined by first calculating the mean shivering intensity of each resting period, then the remaining values above this were averaged again, and the intensity threshold for bursts of shivering was then set at this value (Haman et al., 2004). This was calculated for each participant for each resting period and each individual muscle.

2.4. Statistical analysis

For statistical analyses, we used IBM SPSS Statistics v25 (IBM Corp., USA). Two-way repeated measures analysis of variance (ANOVA) was used to analyze the main effects of time and temperature, and the interaction between ambient temperature and time of the performance and physiological factors (FC_v, RMSE, MFP, T_{sk}, T_{re}, T_{hand}, T_{finger} and heat production). One-way repeated measures ANOVA was used to test for differences in shivering intensity and shivering time over the three resting periods at 8 °C. Residuals were assessed for normality both visually and by applying the Shapiro–Wilks test. Friedman's test was used for analyzing the development within each ambient temperature condition for nonparametric data (PTS, shivering/sweating sensation and thermal comfort), and the Wilcoxon signed-ranks test with Bonferroni corrections was used for paired samples between the two ambient temperatures. Nonparametric data are presented as the median and range, all other data are presented as mean ± SD, and differences were considered significant if $p < 0.05$.

3. Results

All skin temperature measurements decreased over time in the cold compared with the control condition (Fig. 4). T_{sk} decreased 5.5 ± 0.6 °C

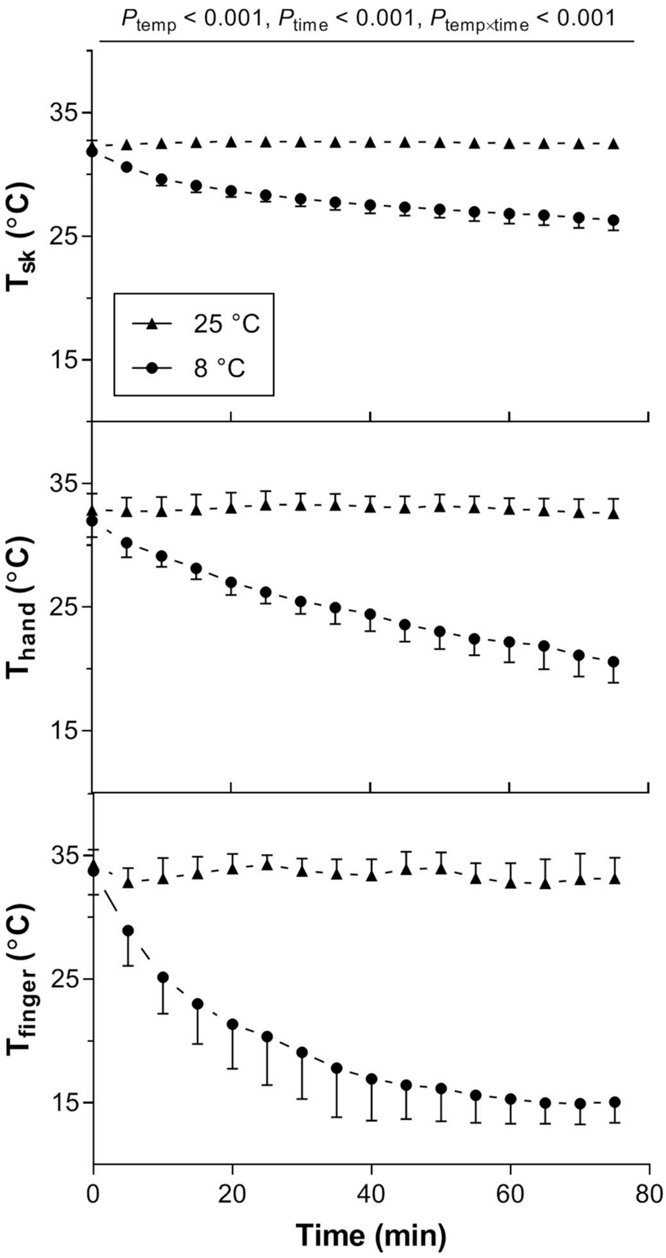

Fig. 4. Mean skin temperature (T_{sk}), hand skin temperature (T_{hand}) and finger temperature (T_{finger}) at control (25 °C) and cold (8 °C) conditions. Values are the mean ± SD. There was a significant main effect of temperature, main effect of time and of interaction between ambient temperature and time for T_{sk}, T_{hand}, and T_{finger}.

from start to end in the cold condition, for T_{hand} the decrease was 11.4 ± 2.0 °C, and for T_{finger} the end temperature was 18.7 ± 2.1 °C lower than at the start. T_{re} stabilized at 36.8 ± 0.2 °C and 36.7 ± 0.2 °C at the end of the baseline resting period in the cold and control conditions, respectively. T_{re} significantly decreased over time ($p < 0.05$) by 0.3 ± 0.2 °C and 0.3 ± 0.1 °C in the cold and control conditions respectively, but there were no significant differences between the two rectal temperatures ($p > 0.05$). In the cold condition, participants felt increasingly colder in both the whole-body and hands, and they reported becoming increasingly thermal uncomfortable (Table 1).

Increased heat production was measured at the last resting period during the cold condition (Fig. 5). No bursts of shivering were measured in any of the muscles for any of the participants. Therefore, all measured shivering was continuous low-intensity shivering. There was an increase in both intensity and duration of continuous low-intensity shivering over time in the cold condition for the upper trunk muscles, but not for the upper limb muscles (Fig. 6). The reported shivering sensation also increased with time for most participants during the cold condition, but no shivering was reported during the control condition (Table 1).

The MFP was very close to that intended at both 10% MVC and 30% MVC. For each test and ambient temperature, the group mean differentiated <0.1% from 10% MVC and <0.5% from 30% MVC with SDs of <0.1% for 10% MVC grip force and of <0.4% for both the 10% MVC grip force and 10% and 30% MVC pinch force. No significant effect of ambient temperature over time was measured for MFP in either task.

The relative variability of force maintenance, measured as FCv, was below 2% for the hand grip task, and below 3% for the key pinch task. There was no significant effect of ambient temperature over time for FCv on either hand grip or key pinch tasks (Fig. 7). However, FCv significantly increased over time at the 10% MVC for the finger pinch task, independent of the two ambient temperature conditions (Fig. 7). No significant effect of ambient temperature over time was measured for force accuracy, measured as RMSE, on either hand grip or key pinch tasks (Table 2). The two ambient temperature conditions in our experiments had no effect on hand grip MVC or key pinch MVC over time, but a decrease in MVC for key pinch from start to end was measured in both ambient temperatures (Table 3).

4. Discussion

The main aim of this study was to evaluate the effect of mild whole-body cold stress on isometric force control during nonfatiguing submaximal hand grip and key pinch tasks. We found that isometric force control during these tasks was maintained during mild cold stress. The cold condition (8 °C) did lead to decreased skin temperatures, continuous low-intensity shivering in the upper trunk, increased heat production, and subjective feelings of cold and shivering. Due to these thermoregulatory defense mechanisms the rectal temperature did not decrease more in the cold than the control condition (25 °C). Because no bursts of shivering were measured, the aim of inducing only mild whole-body cold stress in the cold condition was met. In the control condition, T_{sk} was 32–33 °C for all participants and they felt thermally comfortable. This is the expected response for humans resting in their thermal comfort zone (Kingma et al., 2014). Thus, the participants in the control condition were thermally neutral, in terms of body temperature, heat production activity, and thermal comfort scores.

For the isometric hand grip task, no significant change in force control, measured as force variability and force accuracy, were found between the ambient temperatures. Compared with a previous study using similar whole-body cold stress conditions (Meigal et al., 1998), the tasks either lasted longer or the intensity was higher, with still no detrimental effect on isometric force control for the hand grip task. With no negative effect of cold stress on the isometric force control during key pinch tasks either, this supports the theory that isometric exercise is less temperature dependent than is dynamic exercise (Bergh and Ekblom, 1979; Oksa, 2002; Wakabayashi et al., 2015).

Cooling increases the relaxation time of the contraction coupling mechanism (i.e., prolonged contraction) and decreases the rate of force development (Bigland-Ritchie et al., 1992; Davies et al., 1982; Mallette et al., 2018, 2019) which impairs muscular performance during dynamic exercise (Oksa, 2002; Racinais and Oksa, 2010). However, for isometric exercises, optimal submaximal endurance has been found for muscle temperatures at 27–28 °C (Clarke et al., 1958; Petrofsky and Lind, 1975), and local muscle cooling has not been found to have detrimental effects on force control during submaximal isometric contractions in young adults (Dewhurst et al., 2007; Geurts et al., 2004; Mallette et al., 2018, 2019). Some evidence suggests that to produce the same force when the muscle is cooled, additional motor units are recruited to compensate for the impairment in muscle contractile properties during submaximal isometric contractions (Mallette et al.,

Table 1
Perceptual responses before the resting periods at the two ambient temperatures.

	8 °C				25 °C			
	Baseline	Test 1	Test 2	Test 3	Baseline	Test 1	Test 2	Test 3
Shivering/sweating sensation[a]	**4** **[4, 4]**	**3.5** **[2, 4]**	**3*** **[2, 4]**	**2.5*** **[1, 4]**	4 [4, 5]	4 [4, 5]	4 [4, 5]	4 [4, 5]
PTS: body[b]	**0** **[0, 2]**	**−1*** **[−2, −1]**	**−1*** **[−2, −1]**	**−2*** **[−3, −1]**	0 [0, 2]	0 [0, 2]	0 [0, 2]	0 [0, 2]
PTS: hands[b]	**0** **[−1, 2]**	**−1*** **[−1, 1]**	**−1.5*** **[−3, 0]**	**−2*** **[−3, −1]**	0 [0, 2]	0.5 [0, 2]	1 [0, 2]	0 [0, 2]
Thermal comfort[c]	**1** **[1, 2]**	**2*** **[2, 3]**	**2*** **[2, 3]**	**3*** **[2, 3]**	1 [1, 1]	1 [1, 1]	1 [1, 2]	1 [1, 2]

PTS, perceived thermal sensation.
Data are presented as the median and range [min, max].
Significant ($P < 0.001$) change over time within each ambient temperature condition (Friedman's test) is indicated with bold font.
* Significantly different from paired sample at 25 °C, $P < 0.05$.

[a] 1, vigorously shivering; 2, moderately shivering; 3, slightly shivering; 4, neither shivering nor sweating; 5, some sweating; 6, moderate sweating; 7, heavy sweating.

[b] 3, hot; 2, warm; 1, slightly warm; 0, neutral; −1, slightly cool; −2, cool; −3, cold.

[c] 1, comfortable; 2, slightly uncomfortable; 3, uncomfortable; 4, very uncomfortable.

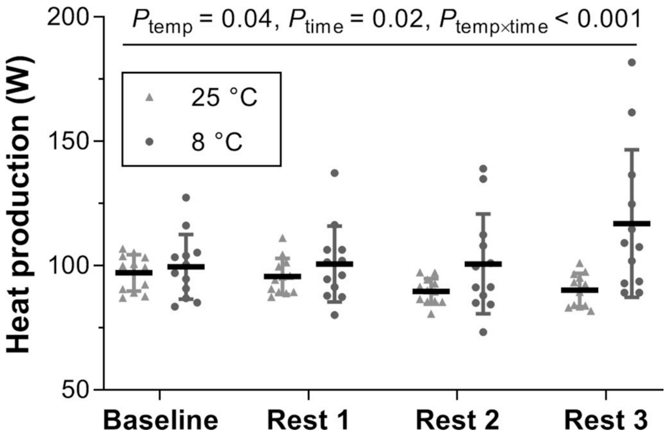

Fig. 5. Heat production at the baseline resting period and at the three resting periods at control (25 °C) and cold condition (8 °C). There was a significant main effect of temperature, main effect of time and of interaction between ambient temperature and time. Mean ± SD are noted by error bars.

2018). Cold-induced prolonged contractions might also help in reducing force variation. Whether there was decreased muscle temperatures in our study is unknown because only skin temperatures were measured. However, given the large drop we recorded in local skin temperature, it is possible that muscle temperatures were reduced.

During the last isometric force tasks, the T_{finger} was 15 ± 2 °C, which is within the limit for expected deterioration in manual and finger dexterity (Ray et al., 2019). Thus, the T_{finger} limit for a decrease in isometric force control must be lower than for manual dexterity tasks. Finding this limit would be of interest but was outside the scope of this study, where the focus was to represent a realistic mild cold stress that one can expect to encounter frequently during leisure and work activities in the cold.

No differences in fatigue, measured as a decrease in isometric MVC force, were found for the hand grip task. MVC force is regarded as a reliable and valid measurement of muscle fatigue (Vøllestad, 1997). Key pinch MVC decreased in both cold and control conditions, with no difference between ambient temperatures. By having a control condition, investigators can distinguish between the effects of the exercise protocol and the ambient temperature. The reason for the decrease in key pinch MVC was not temperature but probably because the protocol for the key pinch task was slightly fatiguing. This is supported by the increased force variation seen over time, independent of ambient temperature, for the key pinch task.

Spending time in the cold condition increased both shivering intensity and shivering time for the upper trunk muscles but not for the upper limb muscles, measured by the use of EMG. The measured shivering in the upper trunk was continuous low-intensity shivering only. This is consistent with the small increase in heat production over time registered in the cold compared with the control conditions. The test leader did not observe any visible vigorous shivering overall, but one participant did report vigorously shivering before the last resting period. Otherwise, the median subjective response showed an increase in shivering, which corresponds to the EMG measures of continuous low-

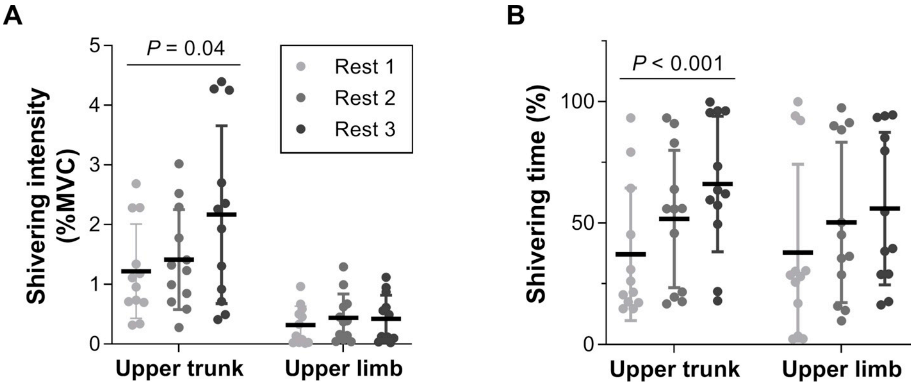

Fig. 6. Change from baseline in shivering intensity (A) and shivering time (B) during the resting periods in the cold condition (8 °C). There was a significant difference over time for shivering intensity and shivering time in the upper trunk. Mean ± SD are noted by error bars.

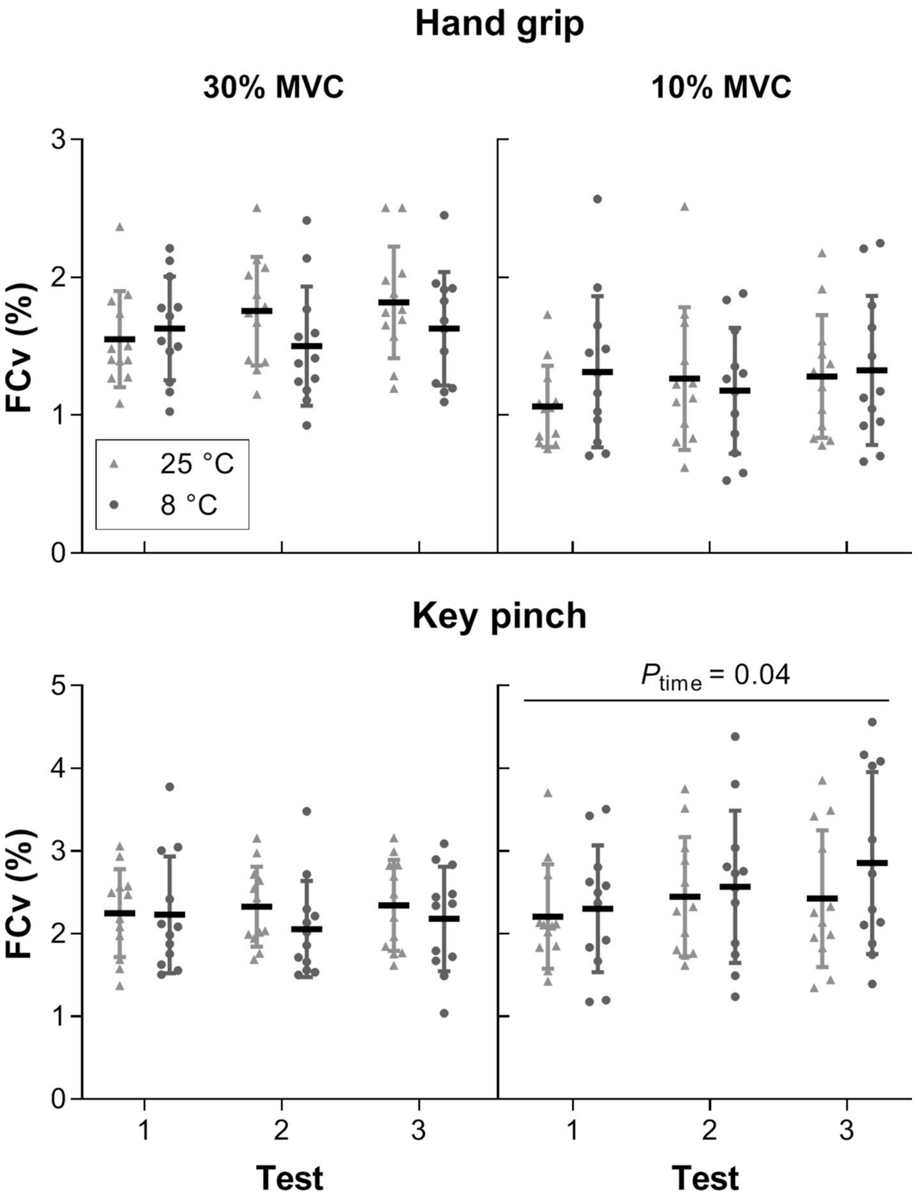

Fig. 7. Coefficient of force variation (FCv) during different motor tasks at three time points during control (25 °C) and cold (8 °C) conditions. There was a significant difference over time for key pinch 10% MVC. Mean ± SD are noted by error bars.

Table 2
Force accuracy measured as RMSE (in N) at the two ambient temperatures.

Target force level	8 °C			25 °C		
	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3
Hand grip						
10% MVC	0.4 ± 0.2	0.3 ± 0.2	0.4 ± 0.3	0.3 ± 0.2	0.5 ± 0.4	0.5 ± 0.4
30% MVC	2.8 ± 1.5	2.2 ± 2.0	2.5 ± 2.3	2.6 ± 1.2	3.0 ± 1.8	2.4 ± 1.5
Key pinch						
10% MVC	0.3 ± 0.2	0.2 ± 0.1	0.2 ± 0.2	0.2 ± 0.1	0.2 ± 0.2	0.2 ± 0.2
30% MVC	0.4 ± 0.3	0.3 ± 0.2	0.3 ± 0.3	0.5 ± 0.3	0.4 ± 0.3	0.4 ± 0.3

MVC, maximal voluntary contraction; RMSE, root-mean-square error.
Data are mean ± SD.

intensity shivering. Shivering has been shown to increase force variability during submaximal isometric elbow flexion at 10% MVC (Meigal et al., 2003), whereas for 20–80% MVC, no effects of shivering were measured. Another study by the same authors showed no adverse effects of shivering on hand grip or elbow flexion at 10% MVC but did show a decrease in isometric force control during shoulder abduction at 10% MVC (Meigal et al., 1998). This shows that force control operated by distal muscles is not reduced by shivering in the central muscles. In combination with the EMG results from these studies, the authors suggest that shivering "coexisted" with voluntary contractions at 10% MVC,

Table 3

Mean (±SD) peak force during maximal voluntary contractions (MVCs) for hand grip and key pinch tasks at the start and end of the tests at the two ambient temperatures.

	8 °C		25 °C	
	Start	End	Start	End
Hand grip (in N)	617 ± 89	615 ± 103	613 ± 92	607 ± 87
Key pinch (in N) [a]	115 ± 22	107 ± 25	114 ± 23	109 ± 22

[a] Indicates main difference over time ($P_{time} = 0.01$).

whereas the shivering was suppressed at 20% MVC and above. Whether bursts of shivering in the upper trunk or continuous low-intensity shivering in the upper limb would have affected the force control results in our study is unknown and outside the aim of the study. However, based on previous studies (Meigal et al., 1998, 2003) it is possible that bursts of shivering would not have adversely affected the isometric force control in our study, because the tasks were operated by distal muscles and half of them had an intensity of >10% MVC.

Some limitations of this study should be considered when interpreting these results. The participants in this study were all young and healthy men, whereas the effect of ambient temperature on force control is important for people of all ages and sexes. Force steadiness declines with age, and females are generally less steady than males, measuring a higher FCv across submaximal forces and most muscle groups (Jakobi et al., 2018). Studies on the effect of cold on force control in females and/or older adults are scarce. However, one study did find that local cooling of the tibialis anterior muscle did not affect FCv during 30 s of submaximal isometric ankle dorsi-flexions at 5%, 10% or 15% MVC for the young females, but the FCv increased with cooling for the older females (Dewhurst et al., 2007). Thus, there is a risk of impairment in the force control of older individuals with varying ambient temperature, but whether this also applies to manual force control needs further investigation.

5. Conclusion

In conclusion, isometric force control during hand grip and key pinch tasks was maintained when participants experienced mild whole-body cold stress compared with when they were thermally comfortable. Mild cold stress was evident as low-intensity shivering in the upper trunk, by decreased skin temperatures, but without a cold-induced decrease in rectal temperature and no high-intensity bursts of shivering. Whereas manual dexterity is reduced by peripheral cooling, this temperature-induced degradation in manual performance does not seem to apply to isometric force control. This indicates that the underlying mechanisms in responding to cold conditions have different consequences for different manual tasks.

CRediT authorship contribution statement

Julie Renberg: Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft, Visualization. **Øystein Nordrum Wiggen:** Conceptualization, Methodology, Writing - review & editing. **Juha Oksa:** Conceptualization, Methodology, Writing - review & editing. **Kristine Blomvik Dyb:** Validation, Investigation, Writing - review & editing. **Randi Eidsmo Reinertsen:** Conceptualization, Supervision, Writing - review & editing. **Karin Roeleveld:** Methodology, Supervision, Writing - review & editing.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jtherbio.2020.102537.

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