Cardiovascular and Thermal Strain during Manual Work in Cold Weather

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ABSTRACT

In some occupations it is hard to protect the hands against the severe weather conditions in wintertime due to the requirement to maintain manual dexterity. Decrease in temperature of the hands increases risk of cold injury and deteriorates muscle function and manual dexterity, which in turn decreases productivity. A series of field and lab studies were performed to investigate cold stress and cold acclimation on the neuromuscular function of the hand. To quantify the cardiovascular and thermal strain during a working day in cold weather (–17.6±3.1ºC (mean±sd)), five line workers (4 male, 1 female, 36.4±4.4 y) from the maintenance crew of New Brunswick Power were equipped with skin thermistors and heart rate monitors and followed for a day (0900h – 1600h). Typical tasks were videotaped and a time log of activities and hand protection levels were recorded. Hand and finger temperature dropped as low as 17.0–24.4ºC and 7.9–12.6ºC, respectively. Average temperatures over the working day period varied from a hand temperature of 24.8–31.4ºC to 21.0–29.8ºC for the index finger. The lowest mean body skin temperature ranged from 21.0–29.4ºC while on average, this was 25.6–34.1ºC. Typical tasks included climbing poles, cutting wires, and shovelling snow. Peak heart rate (HR) was 148–181 b·min^{-1}. Although the measurements took place during a day of relatively mild weather and light activity, skin temperature of fingers and hands decreased to a level that has been previously demonstrated to impair manual dexterity. The intensity level of certain tasks was as high as 82–97% of the age-predicted HR_{max}. It was concluded that alternating high intensity tasks with low intensity tasks demanding manual dexterity, will decrease cardiovascular strain and may improve manual performance by warming the body and hands. This field study was followed up by laboratory experiments that were conducted to investigate the effects of physical activity and a resulting increase in core temperature (±0.5ºC) on cold acclimation and neuromuscular function of the hand. Neuromuscular function of the hand was tested before and after hand cooling in 8ºC water for 30 min while either bicycling at a submaximal level or sitting at rest, before and after two weeks of local cold acclimation (30 min/day, 5 days/week). Neuromuscular tests consisted of tactile sensitivity, hand grip strength, manual dexterity and an evoked twitch force in a custom made myograph. Temperature of core, index finger and hand were recorded daily as well as subjective thermal ratings. Thermal ratings and index finger temperature increased significantly during acclimation days from 1.2±0.7 ('very cold') to 2.1±1.3 ('cold') (P<0.01) and 8.7±0.7ºC to 10.1±1.3ºC (P=0.04), respectively. Neuromuscular function was impaired with cooling and neither acclimation nor an elevation in core temperature had a significant effect on manual performance. Subjective thermal ratings were the first to acclimate even when no improvements in actual temperatures were seen. We conclude that the discrepancy between subjective and actual temperature may pose an additional risk of cold injury on people exposed to repeated cold stress by changing their behavioural thermal regulation response.

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1.0 INTRODUCTION

In outdoor occupations that require manual work it is often hard to protect the hands against severe cold weather conditions. Although heavy insulative clothing may keep the body warm, hands are often exposed because gloves and mittens may impair manual dexterity [9], or the type of task requires people to wear gloves that do not protect the hands properly against the cold. For example, Finnish researchers have reported skin temperatures as low as 8°C in cheeks and fingers of outdoor workers during winter in Finland [2]. Similarly, people who work in the frozen food industry are regularly exposed to this kind of cold stress [4, 17, 20].

Exposure of the hands to cold may result in a decrease in muscle temperature causing a decrement in neuromuscular function [6-8,19], impairment of manual dexterity and performance [3,11], and may cause cold injury or frostbite, reducing work safety and increasing accident rates [2].

However, people can adapt or acclimate to their environment. Some research on people living in cold environments and people being exposed to repeated cold stress has found an enhancement of blood flow to the extremities [1,13,14,16]. It was suggested that the warm blood from the core may warm up the muscles and theoretically improve manual dexterity and tactile sensitivity during work in the cold [5], but this remains largely untested.

Most local cold acclimation studies conducted in laboratories were performed on resting subjects. Occupations that require manual work, often also involve physical activity. Therefore the first objective was to investigate the thermal and cardiovascular strain in a typical outdoor occupation. Secondly, a follow up laboratory study was conducted to investigate the effects of physical activity and a concomitant elevated core temperature on cold acclimation and neuromuscular function of the hand. It was predicted that during manual work outdoors, the cardiovascular strain is fairly high resulting an increase in core temperature and this elevation of core temperature would improve neuromuscular function but decrease local cold acclimation.

2.0 METHODS

2.1 Field Study

The field study was conducted on three separate days in February in New Brunswick Canada (–7 to –15ºC). Five outdoor workers (4 male, 1 female) were followed for one working day. They were selected from the maintenance crew of New Brunswick Power, who are responsible for repair and replacement of faulty high voltage wires wearing rubber gloves during tasks handling 'live' wires. The subjects were instrumented with a heart rate monitor and thermistors taped to the skin of the index finger (T_{if}), hand (T_{fdi}), arm (T_{biceps}), chest (T_{chest}), thigh (T_{thigh}) and calf (T_{calf}) and one thermistor was placed in the ear canal (T_{ear}). Average skin temperature ($\overline{T}_{sk}$) was calculated using Ramathan [18]: $\overline{T}_{sk} = 0.3\ (T_{chest} + T_{biceps}) + 0.2\ (T_{thigh} + T_{calf})$.

The subjects were asked to dress and act as they normally would on an average shift and their clothing ensemble and tasks were recorded.

2.2 Laboratory Study

Eighteen subjects came to the laboratory on ten different occasions (5 times/wk for 2 weeks). *A priori* the subjects were split up into two groups: EXP (4♀, 6♂, age: 24.1±6.9y) and CON (4♀, 4♂, age: 25.1±5.7y). On day 1 and 10 a series of neuromuscular and manual function tests were conducted before and after 30 min of hand cooling while the subject was bicycling on a stationary bike at 50% of their age-predicted maximum heart rate (HR_{max}). Day 2 through day 9 were acclimation days on which the subject immersed their hand in 8ºC for 30 min while exercising (EXP) or sitting still (CON). Temperature of the index finger (T_{if}) and hand (above the first dorsal interosseus muscle; T_{fdi}) as well as rectal temperature (T_{re}) were measured continuously. Every 5 min during hand immersion, heart rate, blood pressure, and subjective thermal sensation (on a scale ranging from unbearably cold to very hot) and thermal comfort (ranging from comfortable to extremely uncomfortable) were measured. On the testing days, grip strength, tactile sensitivity, manual dexterity were tested and twitch characteristics were measured using a custom made myograph which was placed in a climatic box.

3.0 RESULTS

3.1 Field Study

Over the course of the day, the workers were in and out of the cold. While on breaks between tasks, or when driving from site to site, the skin temperatures increased to thermoneutral values. While outside, hand and index finger temperatures dropped as low as 17.0–24.4ºC and 7.9–12.6ºC, respectively. The volunteers were well dressed for the cold environment, resulting in $\overline{T}_{sk}$ ranging from 25.6–34.1ºC over the course of the day. An example of $\overline{T}_{sk}$, T_{if}, and T_{fdi} of one volunteer throughout the working day is shown in Figure 1.

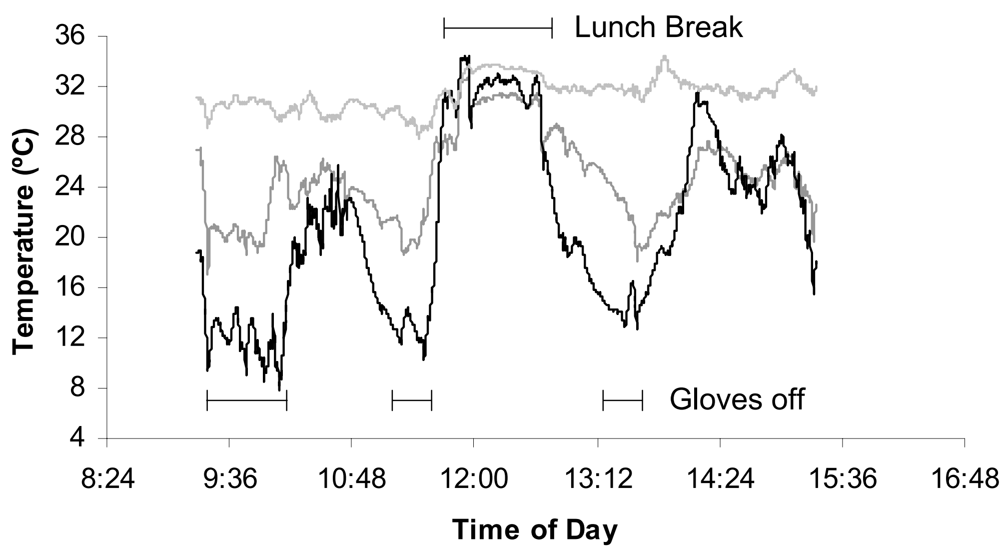

Figure 1: Skin Temperature of the index finger (T_{if}; black), and hand (T_{fdi}; dark grey); and the ear canal (T_{ear}; light grey) during manual work in cold weather.

There were large parts of the day when workers were involved in low intensity activities, such as preparing for the next task or walking to the work site. Heart rates during these periods were relatively low (45–55% HR_{max}). Examples of medium intensity activities included carrying materials to the work site and putting parts together. However, work intensity sporadically spiked during high intensity tasks like shoveling snow to get to a high voltage box or climbing onto a power pole, with peak heart rates reaching 148 – 181 $b \cdot min^{-1}$ or 82 – 97% HR_{max}. HR response of one volunteer over the working day is shown in Figure 2. To gain more experience, the apprentices completed more tasks than the seniors, which is reflected in a higher mean HR response (108.7 and 99.7 $b \cdot min^{-1}$, respectively).

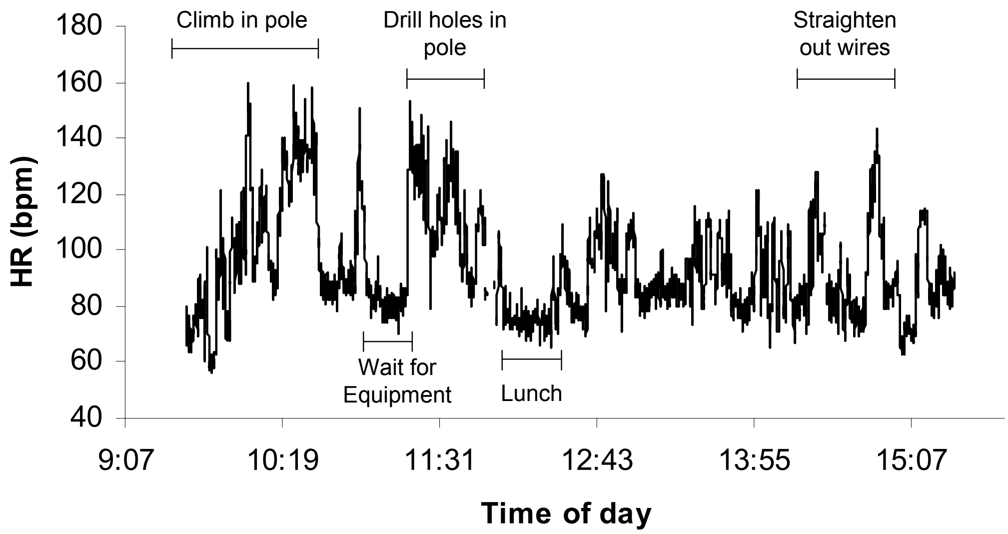

Figure 2: Heart rate response from one worker during manual work in cold weather.

3.2 Laboratory Study

3.2.1 Thermoregulatory Data

During the acclimation days, the rectal temperature increased significantly in the EXP group by 0.49±0.2ºC, while the CON group remained thermoneutral. T_{if} min increased significantly from day 2 (8.7±0.7ºC, mean±SD) to day 6 (9.9±1.1ºC) (P<0.01) and day 9 (10.1±1.3ºC) (P=0.04) but this was not different between the two groups (Figure 3A). Average index finger temperature (T_{if} mean) increased significantly from day 2 (12.4±2.8ºC) to day 9 (15.0±3.0ºC) (P=0.04) and this also was not significantly different between the groups (Figure 3B). There was a large individual variation in onset time (656±69 s) and amplitude of the cold-induced vasodilatation (5.8±0.7ºC) and both were unaffected by acclimation or group. Minimum and average T_{fdi} were also significantly higher on the testing days compared to the acclimation days (P<0.05) for both groups because of the rubber glove worn during the testing days. During the acclimation days, there was a significant decrease in minimum T_{fdi} for the groups combined from Day 2 (10.2±1.5ºC) to Day 9 (9.4±1.1ºC) (P=0.03). Minimum T_{fdi} was significantly higher on Day 3 (10.7±1.9ºC) compared with Day 6 (9.4±1.3) (P=0.02), Day 7 (9.7±1.2ºC) (P=0.05), and Day 9 (9.4±1.1ºC) (P=0.04). There was no significant difference in T_{if} or T_{fdi} between the pre and post tests.

3.2.2 Neuromuscular Data

Grip strength was not significantly different between groups or tests but the difference between testing condition approached significance (thermoneutral: 46.1±13.3 N cold: 44.3±12.5 N) (P=0.06). Tactile sensitivity was unaffected by direct or repeated cold water exposure and not different between the groups. Manual dexterity was significantly impaired in cold condition (thermoneutral: 57.2±13.3 s vs 44.0±11.3 s in cold condition) but unaffected by repeated cold exposure and not significantly different between groups.

Peak twitch force (PTF) decreased gradually with immersion time from 2.4±0.7 N to 1.8±0.8 N after 30 min (P<0.01), but this was not significantly different between groups nor changed after repeated cold exposure. However, the average PTF of the combined groups were significantly higher after acclimation (2.3±0.9 N) compared to before (2.0±0.8 N) (P=0.03). Time to peak (TTP) and half relaxation time (HRT) increased significantly with cooling from 71±8 s to 126±37 s (P<0.01) and 57±9 s to 104±28 s (P<0.01) respectively. This was also not significant different between the groups or after repeated cold exposure.

The relationship between PTF and immersion time and between PTF and T_{fdi} was not significantly different between groups or after repeated cold exposure. There was no change in the relationship between TTP and immersion time or T_{fdi}. The relationship between HRT and immersion time remained the same, only the slope of the relationship between HRT and T_{fdi} was significantly steeper in the control group (–3.6±1.5) compared to the exercise group (–2.6±0.9) (P=0.05). This was not affected by repeated cold exposure.

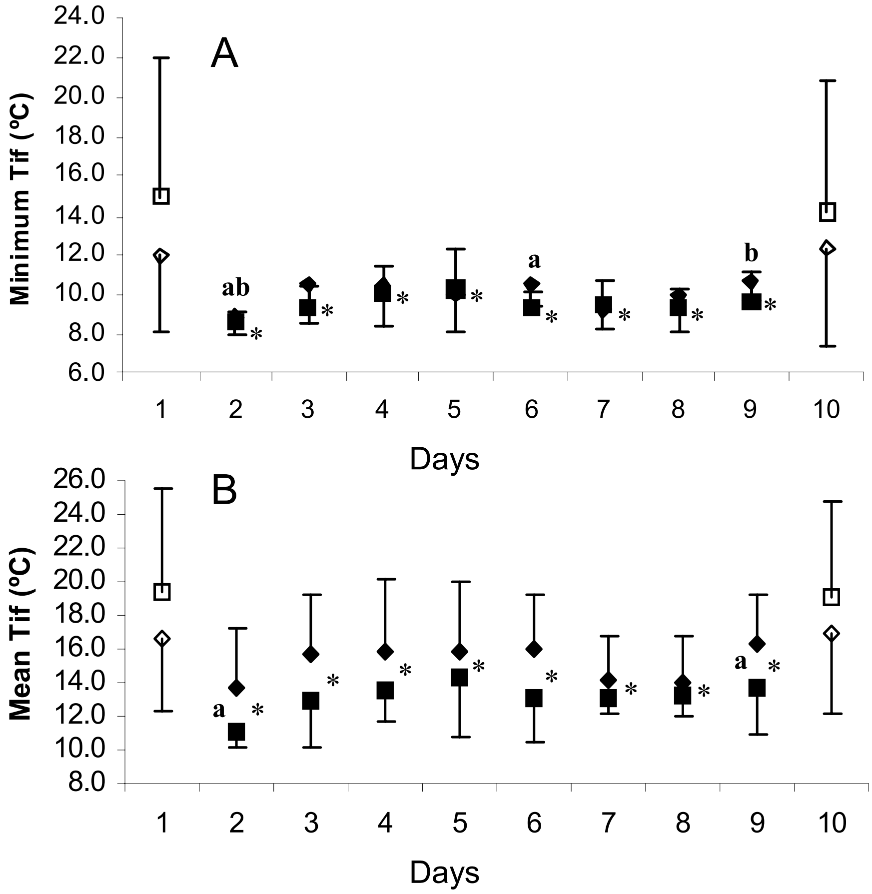

Figure 3: A. Minimum and B. Mean index finger temperature (T_{if}) of the EXP (diamonds) and CON (squares) group during the testing (open) and acclimation (filled) days. *significant difference from testing days (P<0.05). Letters a, and b indicated significant difference from each other (P<0.05).

3.2.3 Thermal Sensation and Thermal Comfort

There was no significant difference in Thermal Sensation (TS) between the two groups. Thermal sensation at 1 min was significantly higher during the testing days compared to the acclimation days (P<0.01) because of the glove. During the testing days, TS at 30 min increased significantly from 3.6±0.6 before to 4.1±1.1 after repeated cold exposure (P<0.01). During the acclimation days, TS at 1 min was significantly lower than at 30 min (P<0.01) but this difference was not significant any more by day 9. TS at 1 min increased significantly from 1.2±0.7 on day 2, to 2.1±1.3 on day 9 (P<0.01). TS at 30 min was the lowest on day 6 (2.6±0.8) and this was significantly lower than on day 10 (4.1±1.1). Figure 4A shows the time course of both thermal sensation and thermal comfort ratings at 1 and at 30 min.

There was no significant difference in Thermal Comfort (TC) between the two groups. Subjects rated their hand significantly more comfortable at 1 min during the testing days than during the acclimation days (P=0.01). An overview of the subjective thermal ratings pre and post repeated cold exposure is shown in Table 2. During the acclimation days, thermal comfort was significantly higher (i.e. less comfortable) at 1 min than after 30 min of hand cooling (P<0.04), but this difference disappeared on day 9. Thermal comfort at 1 min decreased significantly (i.e. more comfortable) from 3.6±1.0 on day 2, 3 and 4 to 2.7±1.2 on day 9 (P<0.01). Thermal comfort at 30 min was higher on day 2 (2.2±0.7) and 8 (2.4±0.9) than during the post test on day 10 (1.6±0.5) (P<0.05). Figure 4B shows the time course of the thermal comfort rating.

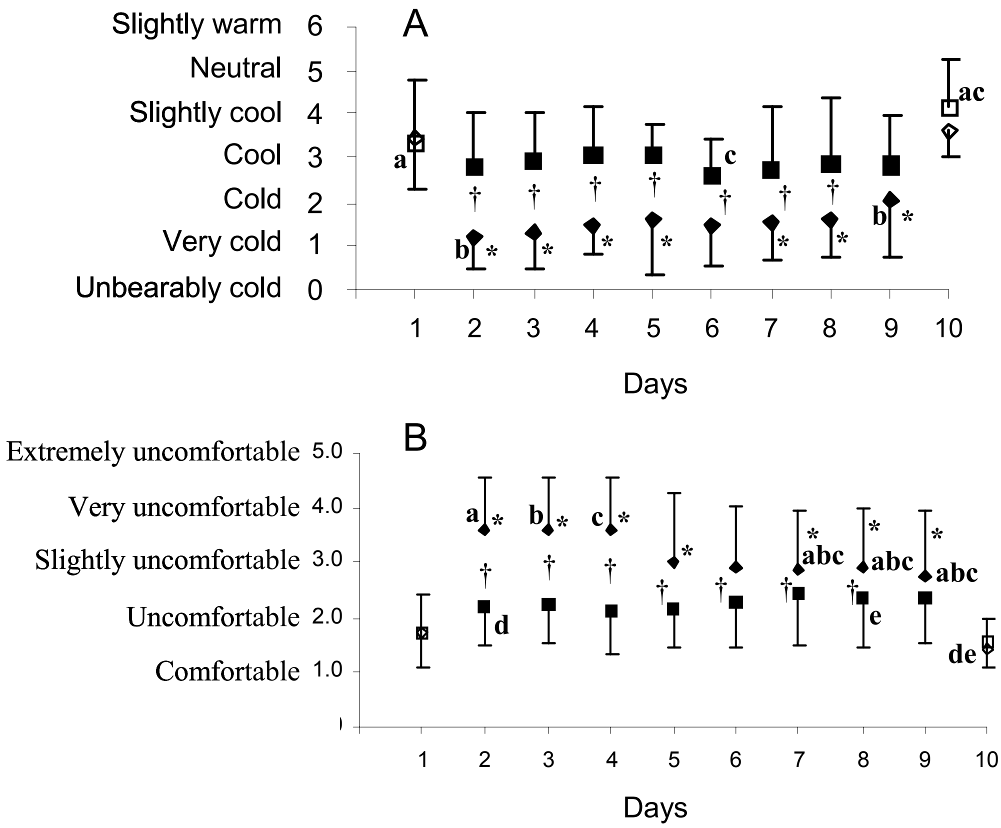

Figure 4: A. Thermal Sensation ratings and B. Thermal Comfort ratings at 1 (diamonds) and 30 min (squares) during the testing (open) and acclimation days (filled). *significant difference with testing days. † significant difference between values at 1 and 30 min. Letters 'a', 'b' and 'c' indicate significant difference between values (P<0.05).

4.0 DISCUSSION AND CONCLUSION

The field study was the first to track the actual cardiovascular and thermoregulatory profiles of power repair line workers during winter in a field setting, thus providing valuable information about the daily stress and strain of workers exposed for prolonged period of time to work in cold outdoor environments with minimal peripheral insulation but a high requirement for manual dexterity. We found that cardiovascular strain was up to 97% of predicted HR_{max} while performing certain tasks such as climbing onto poles and shoveling snow, and also that finger and hand temperatures dropped to levels that could lead to impairment of manual dexterity [3, 12].

The laboratory study showed that an elevated core temperature changed the direct temperature response of the index finger but did not have an effect on local cold acclimation or neuromuscular function of the hand. Although we found a significant increase in skin temperature of the index finger from day 2 to day 9 – a clear sign of acclimation – we did not find a significant difference between the testing days. The insulative glove worn on those days necessary for the neuromuscular function test, decreased the cold stress exposed from cooled air inside the gloved compared with water cooling during the acclimation days.

The additional cold stress due to the thermal conductivity of water is likely to have influenced the temperature response and thermal sensations and comfort, especially in the beginning of the water immersion. This was reflected in warmer and more comfortable ratings of TS and TC at 1 min during the testing days compared to the acclimation days. Interestingly, after 30 min of cold water immersion the difference between testing and acclimation days had disappeared, indicating that the insulating effect of the glove only provided relief in the initial stage of cold exposure.

Neuromuscular function was impaired in the cold condition but did not change after repeated cold exposure. Neuromuscular function is related more to FDI temperature than to index finger temperature [10]. Since we did not find a significant difference in FDI temperature, changes in twitch characteristics were unlikely. Grip strength, manual dexterity and twitch characteristics were all impaired after 30 min of hand cooling as expected, but this impairment was not affected by repeated cold exposure. Only tactile sensitivity was unchanged after 30 min of hand cooling. We tested the tactile sensitivity directly after the hand was removed from the cold water, and it was possible that the hand was already warming up during the test. It is also possible that cold water cooling of 8ºC, used in the present study, is less severe than the method of –22ºC air cooling that Morton & Provins [15] had used when they reported a significant degree of impairment in sensori-motor tasks after cooling. Morton & Provins [15] also found that most subjects showed little impairment in tactile discrimination above finger skin temperatures of about 8ºC, colder than the average finger temperature during the tactile sensitivity test of ~18ºC in the present study.

Comparing the pre-acclimation data from this study with our previous research in which the subjects were sitting still, exercise had a direct effect on the neuromuscular function of the hand during peripheral cooling. The slope of the relationship between TTP and HRT versus immersion time was steeper in the resting group indicating a more rapid deterioration of neuromuscular function. The relationship between HRT and T_{fdi} was also different between the two groups with a steeper slope in the resting group, again indicating faster cooling and more rapid deterioration of neuromuscular function. There was no change in this relationship after repeated cold exposure. Although exercise or the resulting elevated core temperature did not improve the FDI temperature, it improved neuromuscular function indirectly by changing the relationship between HRT and T_{fdi}. It is possible that skin temperature above the FDI cannot be generalized to the whole hand and that the increase in blood flow and temperature in the index finger during CIVD does affect the deeper tissues of the hand muscles. However, the FDI muscle is a small muscle and Ranatunga et al. [19] found a close and linear relationship between the skin temperature above the FDI and muscle temperature of the FDI. Therefore it is not likely that FDI muscle temperature changed in a different pattern than T_{fdi}.

In summary, power line repair work produced significant cardiovascular strain in the workers we tracked, with intensities peaking at 85 – 97% of age-predicted maximum. While average skin temperature of the body was well maintained in the majority of subjects tracked, finger and hand temperature decreased to a level that may impair manual dexterity and risk cold injury, suggesting that insulative clothing and prolonged natural cold exposure over the course of a winter did not protect these workers from local cold strain. In the laboratory we found that an elevated core temperature of ~0.6ºC during repeated cold water immersion changes the direct temperature response during cold water immersion but does not affect local cold acclimation responses. Neuromuscular function is indirectly improved during exercise thus counteracting the deteriorating effect of cold exposure.

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