Työterveyslaitos
Arbetshälsoinstitutet
Finnish Institute of Occupational Health

TIETOA TYÖSTÄ

SmartPro – Smart protective solutions for industrial safety and productivity in the cold

WORK PACKAGE 2: SMART PROTECTION OF HANDS IN THE COLD

WORK PACKAGE 3: MANAGEMENT AND DISSEMINATION

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Photos: Kirsi Jussila, Sirkka Rissanen and Jenni Kaisto
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This publication has been accomplished with the support by the Finnish Work Environment Fund. This project has been part of SAF€RA program.

ISBN 978-952-261-818-4 (nid.)
ISBN 978-952-261-817-7 (PDF)

Juvenes Print, Helsinki, 2018.

TIIVISTELMÄ

Ympärivuotinen teollinen toiminta pohjoisilla alueilla tuo haasteita teollisille prosesseille sekä heikentää työntekijän lämpömukavuutta, suorituskykyä sekä työterveyttä ja -turvallisuutta. Kylmässä työntekijän työkyky ja tehokkuus laskevat sekä virheiden ja stressin määrä kasvaa. Haitat kohdistuvat erityisesti kehon ääreisosiin, varsinkin sormiin ja käsiin, jotka jäähtyvät ensimmäisenä ja eniten.

SmartPro-hankkeen päätavoitteena oli vähentää jäähtymisen aiheuttamaa toimintakyvyn laskua ja siihen liittyviä virheitä työssä. Hankkeen tavoitteena oli kehittää uusia ratkaisuja kylmäriskien yksilölliseen ja jatkuvatoimiseen hallintaan. Projektin tavoitteena oli kehittää työntekijän sormien lämpötilojen jatkuvaan monitorointiin perustuva, käsineisiin integroitava, lämmitysjärjestelmä, joka säilyttäisi sorminäppäryyden niin hyvänä kuin mahdollista.

Hankkeessa määritettiin kylmässä käytettävien älykkäiden ja lämmitettävien käsineiden tarpeet ja raja-arvot kirjallisuuden, kohderyhmän haastattelujen sekä työpajojen perusteella. Lisäksi käsien yksilöllistä jäähtymistä selvitettiin lämpöfysiologisin mittauksin. Käsineiden lämpöominaisuudet ja lisälämmöntarve mitattiin käden lämpömallin avulla säähuoneessa. Käsineiden vaikutusta käsien toimintaan mitattiin hyödyntäen useita yleisesti käytössä olevia sorminäppäryyteen ja voimaan perustuvia menetelmiä. Lopulta kehitettyjen lämmitettävien käsineiden toimivuus selvitettiin mittaamalla käsien ja sormien iholämpötilat kylmissä oloissa.

Hankkeen tulosten pohjalta luodun SmartPro-konseptin avulla voidaan tunnistaa kylmästä erityisesti haittaa kokevat henkilöt ja kohdentaa älykkäät erityisratkaisut niitä erityisesti tarvitseville työntekijöille. Lämmitettävät ja sensoripohjaiset ratkaisut käsien ja sormien toimintakyvyn turvaamiseksi pidentävät turvallista ja tehokasta työskentelyaikaa kylmissä oloissa. Lisälämmityksen tarjoaminen herkästi jäähtyville työntekijöille myös tasa-arvoistaa työntekijöiden mahdollisuuksia työskennellä kylmissä oloissa.

Työterveyslaitos toteutti hankkeen yhteistyössä norjalaisen SINTEF tutkimusorganisaation kanssa. Hanke kuului Saf€ra-ohjelmaan ja rahoittajana Työterveyslaitoksen toiminnassa oli Työsuojelurahasto.

ABSTRACT

Year-round activity involves challenging climatic conditions for the industries in the North. Especially in the winter cold disturbs not only the machinery of industrial processes and vehicles, but is also very crucial factor to reduce worker's thermal comfort, performance, and occupational health and safety. In the cold, work capability and productivity decrease, the risk of mistakes and errors increases and stress level elevates. Peripheral body parts, such as hands, are the first to cool when humans are exposed to cold resulting in reduced manual and psychomotor performance.

The main aim of the SmartPro project was to prevent physical impairment caused by cooling, and thus prevent errors and disturbances in industrial processes due to reduced human performance. The detailed aims were to create new solutions for early warning, dynamic risk monitoring and management of cold related risks for individual workers while working in cold conditions. The project aimed to develop interactive heating gloves that continuously monitor and control worker's finger skin temperature and allows optimum finger dexterity.

The requirements and limit values for optimal and smart heating cold protective gloves were determined based on literature review, target group interview and workshops. Individual differences in hand and finger cooling were measured by thermophysiological methods. Required additional heating and thermal properties of the developed gloves were measured in laboratory conditions by using thermal hand model. Effects of the gloves on hand and finger performance were measured using several different commonly used methods based on finger dexterity and force. Finally SmartPro heating glove system was validated by physiological tests.

Based on the obtained results SmartPro concept was developed to recognize workers, who are sensible to excess cooling in the cold. With the help of the concept special solutions of additional heating system can be directed to persons whose fingers are cooling fast. Sensor-based heating systems for maintaining fingers skin temperatures, and thus dexterity and performance, prolong the safe and efficient working time in the cold. Additional heating of fingers equalize possibilities of individuals to work safely in the cold climate.

The project was carried out in co-operation with the Finnish Institute of Occupational Health and SINTEF research institute from Norway. The project was part of Saf€ra program and the work of the Finnish Institute of Occupational Health was financially supported by the Finnish Work Environment Fund.

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PROJECT DESCRIPTION

A significant increase in human activity in the Arctic is expected. Several European countries are involved in Arctic business through natural resources, oil and gas, mining, fisheries, the growing tourism sector, transport and navigation as well as technology suppliers and developers for those fields. Year-round activity involves more challenging climatic conditions for the industries in the north than in the areas further south.

Working in cold climates involves various effects on work, health and performance. The degree of cold exposure is essential for the severity and risks associated with the exposure. Cold environment disturbs not only the machinery of industrial processes and vehicles, but is also very crucial factor to reduce worker's comfort, performance and safety. In the cold, work capability and productivity decrease and the risk of mistakes and errors increases. A high level of comfort, performance and safety is required in all outdoor occupations during cold season. Peripheral or uncovered body parts, like hands and fingers, are the first to cool when humans are exposed to cold resulting in reduced manual and psychomotor performance.

To prevent disturbances in industrial processes caused by reduced human performance and increased number of mistakes and errors in cold, there is a need for improved cold risk monitoring systems.

Project "SmartPro - Smart protective solutions for industrial safety and productivity in the cold" aimed to develop novel solutions for improved safety, work capability and productivity of workers during operations in the cold climate by sensor-based monitoring, early warning of critical levels of cold and smart heating systems. The project aimed to create safe and cost effective monitoring system for detecting risks at an earlier stage (e.g. degradation in manual performance, frostbite) and allowing for monitoring at an individual level. Smart solutions will be integrated to a protective workwear jacket and novel designed gloves. Novel glove solutions and improvement of existing monitoring systems were aimed to lead longer continuous outdoor working time and safe industrial process in the future.

Project consist of three (3) work packages (WP):

WP1 – Indication of critical level of cold (Corresponding partner: SINTEF)

WP2 – Smart protection of hands in the cold (Corresponding partner: FIOH)

WP3 – Management and dissemination (Corresponding partner: FIOH)

In this report WPs 2 and 3 lead by FIOH are reported in detail and summary of the WP1 is in the Annex 1.

Work Package 2: Smart protection of hands in the cold

The aim of this part of the study was to develop novel gloves which have new design and optimal thermal insulation supported by auxiliary smart heating system and which could maintain maximal manual performance although worn on.

The key elements were maximal manual performance combined with optimal balance between thermal insulation and smart auxiliary heating. Protective properties of gloves against cold, wind, and water, can be then customized depending on the needs of industry.

Activities of WP 2 is illustrated in the Figure 1 and it consisted of five (5) subtasks:

- Task 1 Determination of requirements for manual performance and optimal cold protection
- Task 2 Development of glove prototypes
- Task 3 Integrating smart heating system
- Task 4 Material and physiological testing
- Task 5 Validation of glove prototypes.

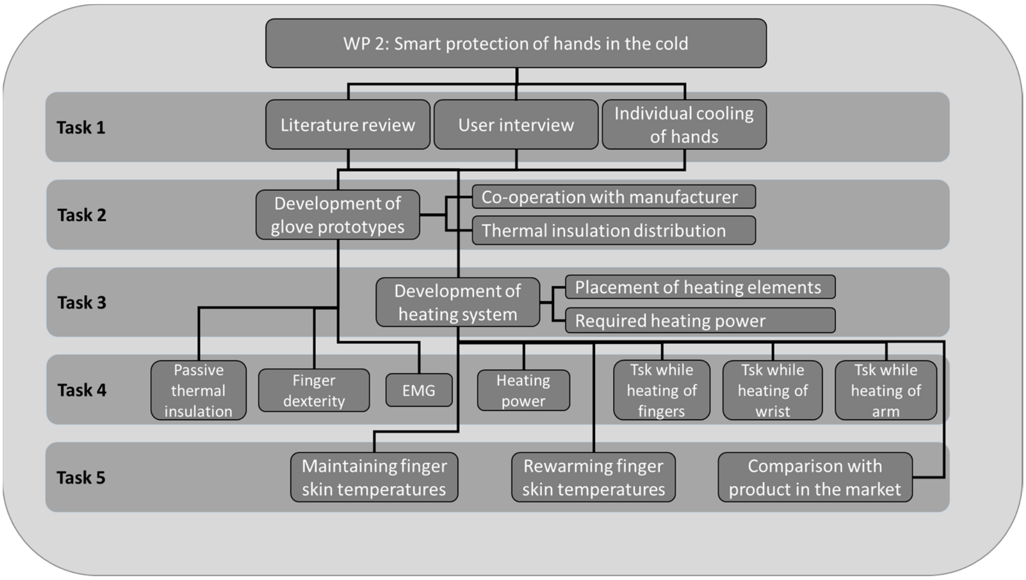

Figure 1. Activity chart of the WP 2 in the SmartPro project.

Work Package 3: Management and dissemination

In the WP3 all the activities of the partners and overview the project progress were coordinated. Activity of this package was to form a consortium agreement that provided day-to-day co-ordination of the project within the deadlines and the budget constraints, as well as to promoted high quality research, assisted partners with the exchange of information, and promoted collaboration between partners. Reporting of the progress was provided according to the regulations of the each financer.

Dissemination of the obtained new information and project results were aimed to deliver to stakeholders, such as mining, petroleum, construction, fisheries, through workshops and seminars, as well as other researchers through conferences, workshops, papers and reports. The WP3 organized workshop-type regular meetings between partners both in situ consisting cooperative working, integration of knowledge from all WPs, and communication with stakeholders. Additional meetings via video connections were organized regularly. One project member participated annually in the Saf€ra symposiums.

TASK 1 DETERMINATION OF REQUIREMENTS FOR MANUAL PERFORMANCE AND OPTIMAL COLD PROTECTION

The aim of this task was to determine critical skin temperature limits for manual performance and requirements for protection of hands in the cold based on existing knowledge and user interviews and studies.

1.1 Literature review

In the years ahead, a significant increase in human activity in the Arctic is expected. Several European countries are involved in Arctic business through natural resources, oil and gas, mining, fisheries, the growing tourism sector, transport and navigation as well as technology suppliers and developers for those fields. Year-round activity involves more challenging climatic conditions for the industries in the North than in the areas further south.

Working in cold climates involves various effects on work, health and performance. The degree of cold exposure is essential for the severity and risks associated with the exposure. Cold environment disturbs not only the machinery of industrial processes and vehicles, but is also very crucial factor to reduce worker’s comfort, performance and safety. In the cold, work capability and productivity decrease and the risk of mistakes and errors increases. A high level of comfort, performance and safety is required in all outdoor occupations during cold season, such as petroleum industry, mining, construction work, and fishery. To prevent disturbances in industrial processes caused by reduced human performance and increased number of mistakes and errors in cold, there is a need for improved cold risk monitoring systems.

Peripheral body parts like hands are the first to cool when humans are exposed to cold (Geng et al., 2006). There are four basic reasons for that: 1) hands have large surface area to loose heat and small mass to produce heat, 2) in whole body cooling the circulation of peripheral body parts is decreased to minimize heat loss, 3) thermal insulation of handwear is often smaller than required to make it possible to handle the tools, and 4) handwear is sometimes temporarily even removed. Consequently, manual performance (composed of tactile sensitivity, force production, coordination of gross and fine movements and manual dexterity) of the worker decreases in early stage of cooling in the cold (Geng et al., 2006). Moreover, hand cooling causes discomfort and eventually cold pain which disturbs mental and psychomotor processes. Also cold protective handwear decrease manual performance especially in tasks where good tactile sensitivity and finger dexterity are needed (Jussila et al., 2013). Use of thin contact gloves under the thicker cold protective gloves is one solution to maintain required manual performance. However, frequent doffing and donning of gloves is not practical in industrial work.

This literature survey provides documentation on crucial parameters for hand function, manual and finger dexterity, tactile sensations and grip force in cold environments as well as parameters of cold protective gloves and their functionality in these conditions. The presented literature include relevant knowledge for developing a smart protection of hands in the cold.

1.1.1 Hand function and manual dexterity

Hand function and manual dexterity are critically important for optimizing work performance and safety (Muller et al. 2014). Several studies have demonstrated significant and progressive impairments in fine and gross manual dexterity induced by local cooling along with rapid impairments of muscular function upon exposure to cold environment. Proposed mechanisms involve nerve conduction velocity, finger tactile sensitivity, synovial fluid viscosity and blood flow, thermal state of the small muscles of the hand as well as between-finger sensory integration.

Recently Jones and Lederman (2006) described the hand function using a continuum, with primary sensory functions at one end and primary motor functions at the other. They are separated into four categories:

1) Tactile sensing is the stimulation of a passive hand, and gives information such as surface texture and temperature.
2) Active haptic sensing involves the voluntary movement of the hand, and sensory inputs are "provided by the stimulation of receptors embedded in skin, muscles, tendons and joints".
3) Grasping (prehension) is primary a motor function, but uses sensory feedback to precisely control movements and forces.
4) Non-prehensile skilled movements include gestures and non-grasping activities such as pressing keys.

1.1.2 Tactile sensation

Tactile sensation is needed to sense the structure and texture of handled objects. Tactile sensitivity is based on function of superficial tactile receptors. Decrement in manual dexterity due to loss of tactile sensation is evident at finger skin temperatures below 8°C because a nervous block occurs at skin temperature of 6-7°C. According to numerous studies tactile sensitivity is significantly reduced at finger skin temperatures of 6°C (Morton and

Provins 1960), 8-10 °C Havenith et al. 1992, Stevens et al. 1977) and even at 12-18°C (Brajkovic et al. 2001) and below 20°C (Wiggen et al. 2011). Cooling of core body temperature may also result in impaired tactile sensation (Cheung et al. 2008).

Touching cold surfaces bare handed rapidly decreases skin temperatures of the hand resulting in onset of numbness within seconds or minutes depending the surface material and temperature (Geng et al. 2006). Risk of skin damage is greater if material has high thermal conductivity such as metallic objects.

1.1.3 Manual dexterity in the cold

Manual dexterity is used to evaluate hand function. Manual dexterity has been defined as a motor skill that is determined by the range of motion of arm, hand and fingers and the possibility of manipulation with hand and fingers (Heus et al. 1995). Nerves, muscles, joints and ligaments are all involved in manual dexterity.

Roughly, dexterity can be briefly classified into two types: gross and fine. The former is the gross movement of hands, fingers and arms and latter is defined as the ability to coordinate finger movements in performing fine manipulations. Reduction in manual dexterity may lead to an increased number of accidents.

Four factors play a role in determining an individual's manual performance in response to cold: climatic factors, personal factors, metabolic rate and clothing insulation (Daanen 2009). According to Havenith et al. (1995) reduction of manual performance due to cold exposure is mainly due to the effects of cold on muscles and joints.

Finger and hand (manual) dexterity is significantly reduced when skin temperature of fingers decreases below 13 °C (e.g. Clark 1961, Daanen 2009, Gaydos and Dusek 1958, Lockhart et al. 1975, Rissanen et al. 2001). If the cooling rate is slow reduction may be seen already at the finger temperature below 19 °C (Lockhart et al. 1975) and results in greater decrement in performance compared with faster rate of cooling (Clark and Cohen 1960). Performance decrement of fine motor tasks is greater and more sensitive to cooling than that of gross motor tasks (Giesbrecht et al 1995). Short-term hand and forearm cold-water immersion resulted in rapid and progressive impairment of both fine and gross manual dexterity (Cheung et al. 2003).

Manual dexterity decrements are due almost entirely to the local cooling of tissue. Body can be cooled to uncomfortable state without affecting the dexterity if fingers and hand are maintained warm (Gaydos 1957). On the other hand, if body core temperature is also cooling together with hands and fingers manual dexterity and tactile sensation are impaired (Cheung et al. 2008). Mean body temperature (T_b) may be correlated with dexterity if T_b calculation is also based on finger and toe temperatures (Daanen 2009). The change in body heat content (ΔH_b) provides better indicator of the relative changes in extremity temperature and hand function during cold exposure compared with either core temperature or rate of body heat storage (Brajkovic et al. 2001). Flouris et al. (2006) stated that the best indicator of hand function is change in H_b (ΔH_b) followed by finger temperature. High body heat content (H_b) (Brajkovic et al. 1998, Brajkovic and Ducharme 2003) or increasing H_b before and throughout a cold exposure (Flouris et al. 2006), effectively can prevent finger temperatures to decrease and maintain manual performance in the cold. However, increasing H_b during cold exposures requires active heating of torso or moderate to heavy exercise. For example, heating torso skin up to 42°C by heated vest can maintain finger temperatures above 22°C, and finger blood flow as well as finger thermal comfort higher than without the heating during cold exposure (Brajkovic and Ducharme 2003). High thermal insulation of clothing is not enough to keep fingers warm (Daanen 2009, Shitzer et al. 1998).

Circulation in the fingers is reduced in the cold due to vasoconstriction. Finger blood flow can be reduced to 1:2.5 at finger temperature of 15°C in comparison to 31°C (Glitz et al. 2005). Reduced blood flow decreases finger temperatures. However, finger dexterity might be maintained despite a low finger blood flow if finger temperature is at a high level (28-35°C), forearm muscle temperature above 30°C and the change in body heat content is not too low ($\geq$ -472 kJ) (Brajkovic and Ducharme 2003). Strong vasospasm response in fingers, such as in Raynaud's phenomenon, results in greater reduction in finger dexterity compared to normal response in the cold (Delp and Newton 1996, Rissanen et al. 2001).

Joint movements in the fingers are affected by the increased viscosity of synovial fluid due to cooling. Impairment in the dexterity is greater when the joint movements are larger such as during maximal flexion of fingers (LeBlanc 1956).

In general cold habituation (most common form of acclimatization) reduces pain, cold sensation and enhances circulation in the extremities. It seems, however, that cold habituation does not improve manual dexterity, although smaller reduction in finger temperature, a lower metabolic rate, less hand pain (Muller et al. 2014) and according to Geurts et al. (2005) may even put the hands a greater risk of cold injury when exposed to the cold.

The gender effect is greater on gross than on fine dexterity. Males have better gross dexterity possibly due to the greater hand and finger strength and faster hand movements (Chen et al. 2010). Aging decreases manual dexterity and peak precision grip force generation and cold further decreases these hand functions (Tajmir et al. 2013).

Furthermore, time of day may affect finger temperatures. Ozaki et al. (2001) found that fingers were warmer at night sift than at afternoon sift during the work in a cold storage. Nevertheless, manual dexterity was decreased more at night sift indicating that circadian rhythm induced variations such as in core temperature and blood pressure might have influence on manual performance.

Wind together with cold exposure enhances the cooling of fingers by increasing the convective heat loss and shortens the predicted times to freezing (Teichner 1957, Oakley 1990, Shitzer et al. 1998a). Face protection may maintain warmer finger temperatures and warmer thermal sensation but did not prevent impairment of manual dexterity compared to without face protection in the cold and windy conditions (O´Brien et al. 2011). Thermal state of the whole body has influence on peripheral temperatures. Pre-cooled subjects showed 4-6 times greater cooling rate of hand and fingers than normothermic subjects (Imamura et al. 1998).

Light exercise is insufficient to keep the hands warm in spite the core and mean skin temperatures are maintained in thermal comfort (Glitz et al. 2007). On the other hand, Imamura et al. (1998) reported that physical exercise significantly increased finger temperatures and partly restored manual performance in the cold. According to Muller et al. (2010) especially continuous exercise seems to be more effective than interval exercise at increasing finger temperature and maintain better dexterity.

1.1.4 Hand grip

Cooling of forearm in 5 °C water for 2 min decreased hand grip strength by 13%, while cooling of unprotected hand grip strength decreased by 16 % (Vincent and Tipton 1988). The effects of cold on hand grip strength may be negligible even when the hand skin temperature is below 10°C (Glitz et al. 2007). Digit cooling resulted in higher grip force against the hand-held object. This impaired economical scaling of grip force level is thought to be a result of reduced sensory feedback from the grasping fingers during cooling (Nowak and Hermsdörfer 2003). During long-term cold weather operations grip strength has been reported to decrease by 4% (Marrao et al. 2005) and also nerve conduction velocity to be reduced (Marshall 1972). Combination of decreased body temperature, continued discomfort and peripheral tissue cooling impedes performance of the arm (Giesbrecht and Bristow 1992). Drop in core temperature alone did not result in impaired grip force with cold hands (Cheung et al. 2008). The peak grip pressure is distributed in index fingertip (Dong et al. 2015).

1.1.5 Modifying factors increasing the individual cold sensitivity of hands

Several factors affect the individual cold sensitivity of hands, e.g., anatomical, circulatory and neurological features, aging, number or severity of previous cold exposures, previous injuries, physical activity and some non-thermal environmental factors. Recognition of cold sensitive individuals is important for proper preventive measures.

Poor finger circulation: Because of the small muscle mass of the hands, and therefore low local heat production, the heat balance of hands and fingers depend on circulation

(Cheung 2015). Hence all factors diminishing hand and finger circulation increase cold sensitivity. Raynaud phenomenon (RP; the enhanced digital vasoconstriction in response to cold) is associated with lower finger temperatures, impaired sensory perception and decreased manual performance in cold (Rissanen et al. 2011). Moreover, Giurgea et al. (2015) showed that in patients with RP, the cold-induced decrease in skin temperature was inversely related to and body mass index (BMI) but such correlations were not observed in controls. Interestingly, the cold-induced change in skin perfusion was not related to age or BMI in either group. Vibration induced white fingers (VWF syndrome or hand arm vibration (HAVS syndrome)) also decrease finger circulation in cold and delays the rewarming (e.g. Ye and Griffin 2016).

Thin fingers: Due to the large surface area – mass relationship fingers are susceptible to loose heat. Skin temperature of fingers decreases linearly with finger circumference in both genders. Although females usually have thinner fingers than males, the average finger temperatures are the same in both genders because the relationship between finger circumference and finger temperature is different in females and males (Rissanen et al. 1993.

Aging: Aging decreases peripheral circulation and impairs also manual performance. Tajmir et al. (2013) showed that older individuals do not perform as well as younger persons across the battery of tests, with cold temperature further degrading their performance in dexterity tasks and peak precision grip force generation.

Slow recovery due to autonomic nervous system function: The individual differences in rewarming rate of hands has correlations with autonomic nervous system function: In heart rate variability (HRV) analysis normal rewarmers had higher power for low-frequency and high-frequency components during the cold provocation test (Brändström et al. 2012). Autonomic nervous system affects temperatures by adjusting the level of vasoconstriction or vasodilatation.

Southern ethnicity: Maley et al. (2014) investigated the effect of extremity cooling on skin blood flow and temperature between Caucasian (CAU), Asian (ASN) and African AFD) descents. Vasoconstriction and vasodilatation occurred at a warmer finger temperatures in AFD during cooling and warming compared with CAU. In the CIVD (cold induced vasodilatation) test, average skin blood flow during immersion was greater in CAU than ASN and AFD. Following immersion, skin blood flow was higher and rewarming faster in CAU compared with AFD, but neither group differed from ASN. Maley et al. (2014) conclude that AFD experienced a more intense protracted finger vasoconstriction than CAU during hand immersion, whilst ASN experienced an intermediate response.

Repeated cold exposures: Earlier information has suggested that cold adaptation caused by repeated exposures to cold suppresses vasoconstriction and facilitate vasodilatation. However, Daanen et al. (2012) and Cheung and Daanen (2012) have suggested that repeated cold exposure of the fingers does not lead to favorable adaptations, but may instead increase the injury risk. Moreover, Muller et al. (2014) have suggested that cold habituation does not improve manual dexterity during rest and exercise in 5 °C.

Injuries: Earlier cold injuries have neurosensory sequelae, in terms of abnormal thermal and/or vibration perception thresholds, may last at least 4 months after the initial injury. Symptoms such as pain/discomfort at cold exposure, cold sensations and white fingers may persist at least 4 years after the initial injury (e.g. Carlsson et al. 2014). Deeper cold injuries may damage tissue circulation and therefore decrease finger temperatures in cold. After traumatic hand injuries cold-induced symptoms are reported in more than 30 % of cases during long time from injury (Novak and McCage 2015).

Insufficient physical work: Physical exercise is the most efficient way to increase metabolic heat production. Rintamäki et al. (2004) showed that an exercise level of ca. 50 % from maximum, with rectal temperature exceeding 37.6°C, is required in outdoor exposures to cause peripheral vasodilatation and warming of peripheral temperatures, including hand and finger temperatures. Muller et al. (2011) also suggested that moderate exercise in general can cause subjective feelings of warmth and less hand pain in people acutely exposed to moderate cold.

On the contrary to the beneficial effects of dynamic exercise or mixed exercise with predominant dynamic component, isometric handgrip exercise in cold has negative effects: it increases blood pressure and induces a significant increase in aortic hemodynamic markers, which may evoke adverse cardiovascular events (Koutnip et al. 2014).

Hypoxia: The study of O'Brien et al. (2015) provided no evidence that hypobaric hypoxia increases risk of cold injury. They suggested that previous findings of blunted finger temperatures at altitude are likely due to the lower ambient temperature that typically occurs at higher elevations. Keramidas et al. 2015) showed that acute exposure to normobaric hypoxia does not aggravate the cold-induced drop in hand temperature of normothermic males. However, hypoxia markedly impairs the rewarming responses of the hand.

1.1.6 Cold protective gloves and dexterity

Cold protective gloves protects fingers and hand against cooling. General requirements for all type of protective gloves are determined by the standard EN 420 (1994). This standard determines requirements e.g. for ergonomics, sizing, construction, visibility, maintenance, comfort of the protective gloves. Standard (EN 511: 2006) for protective gloves against cold determines requirements for protective gloves against convective and contact cold.

Construction of the cold protective gloves is often multilayered (Herman et al., 1992). Thermal liner provides thermal insulation, moisture barrier is located between the liner and outer layer that is supposed to protect against external hazards e.g. mechanical or chemical hazards.

Based on the surface area and the air content between fingers, mittens are warmer design than gloves (Abeysekera and Bergquist, 1996). However, mittens cause a large loss of dexterity comparing to gloves. Glove designs are develop to increase finger dexterity by combining mitten and glove or by leaving part of the finger uncovered. In the studies of Hunt et al. (2014) and Hunt and Wells (2012) mitten style glove and wool glove liner showed lesser drops in skin temperatures of 3rd and 5th digits than five-finger gloves or gloves heated by heat pads.

Heat loss from gloved hand is greatest from thumb and little finger (Sari et al. 2004) therefore these areas require more insulation than other parts. The fit of glove, manipulation of cold tools or materials and wind will considerably modify the local heat loss (Sari et al. 2004).

Gloves impair dexterity independently of temperature. Tactile sensation is impaired by using gloves and also tactual performance is decreased by the wrong size of gloves (Geng et al. 1997b). Clearly, glove thickness modifies the cutaneous sensation (Kinoshita 1990). Moreover, thickness of gloves is essential in the degree of dexterity loss (Bensel 1993, Geng 1997a, Rissanen et al. 2008, Rogers and Noddin 1984). Even thin gloves can decrease finger dexterity by 60% compared with bare-hand performance in the cold (Brajkovic et al. 2001).

Hand maximal grip force was reduced when gloves were worn compared with bare hands (Chang and Shih 2007, Kovacs et al. 2002, Wells et al. 2010) and the thicker glove caused greater strength reduction (Chang and Shih 2007, Wells et al. 2010). Better-fitting gloves result in better transmission of muscular force to grip force (Kovacs et al. 2002). Greater grip force is required with gloves and it is relative to glove thickness (Kinoshita 1999, Willms et al. 2010). Even the task which involved opening the hand to create an aperture required a substantial effort of the muscles of the forearm when powerline maintainers' gloves were used (Wells et al. 2010).

From the dexterity tests O'Connor is more sensitive to different test conditions and discriminates gloves better than Purdue Pegboard test (Berger et al. 2009). When different types of gloves (categorized in fine, medium and coarse dexterity) e.g. O´Connor test is more sensitive to gloves offering fine to medium dexterity range and Minnesota Turning and 2Hand are more sensitive to gloves offering medium to coarse dexterity (Gauvin et al. 2006).

1.1.7 Heated gloves

The application of auxiliary heat on hands (Lockhart and Kiess 1971), liquid-filled bladder warmed by a heat pack (Kempson et al 1988, Pensotti et al. 1995) or electrically heated gloves (Brajkovic and Ducharme 2003, Ducharme et al. 1999) resulted in significantly higher finger skin temperatures and dexterity was maintained or reduction alleviated. Glove warmer (heating pads) seems to be insufficient to maintain hands and finger warmer enough (Hunt et al. 2014). Warming of wrist/palm area has been showed increase in finger temperatures and blood flow in distal parts of the hand (Koscheyev et al. 2001). Castellani et al (2017) showed that direct heating applied to forearm and face reduced the decline in fine and gross manual dexterity by 20-50% at 0°C. Heating temperature set point was 42 °C which resulted in forearm skin temperature of 38.5 °C. However, finger temperature of bare hand decreased to 11.6 °C. Without any heating finger skin temperature was 10.9 °C.

A power input of external heating is suggested to be at least 0.5 W per finger. This heating power in addition to leather and woollen gloves is shown to be sufficient to keep fingertip temperature higher than 10 °C in ambient temperature of 0 °C (Shitzer et al., 1998a). The same amount of heat input was used in addition to simulative spacesuit gloves and it allowed maintaining finger skin temperature above 15 °C in ambient temperature of -140 °C (Ding et al., 2004). However, the limitation of the use of external heating may occur by battery weight or power supply requirements.

1.1.8 Gloves in cold climate

Low ambient or contact temperatures has shown to change mechanical properties of materials when reached close to their glass transition temperature (McCrum et al., 1997). Above the transition temperature polymer materials are rather flexible, but below materials become stiff and brittle. For example, the rate of crystallisation of natural rubber reaches its maximum at -25 °C and -10 °C for neoprene (Fuller et al., 2004). Temperature limit without cracking for leather is defined to be close to -180 °C (Bailey, 1990). However, increased stiffness of leather materials are experienced when temperature has decreased from 0 to -20 °C (Filteau and Shao, 1999; Jussila et al., 2013).

1.2 User interview

Workers in food processing industry (chicken) were selected to user interviews, because more detailed information on requirements of fine motor tasks performed in the cold conditions was needed. Originally was intended to interview also outdoor workers in field of power transmission (mast and pole workers), but cooperation did not realized.

A structured outline for the interview was created. The outline consisted questions related to: background information of the workers and work tasks, work environment and thermal conditions at work, description of manual tasks, description of the used gloves at work, description of the most challenging work tasks and situations, and needs and ideas for development. Five workers were interviewed via video connection.

Work in the food processing industry is performed in ambient temperatures below +8 °C. Draught and high relative air moisture are typical factors as well. According to the interviewed workers, especially hands are vulnerable to cooling due to contact with cold meat products (temperature <+2°C) or metal trolleys that are used to transfer meat in the process. Work itself is generally light manual work, e.g. using scissors and knives while standing but moderate physical activity periods also occurs and which may result sweating. Overall protective clothing consists of jacket and trousers and workers wear mainly their own garments underneath them. Hands are covered by undergloves made of cotton or acrylic, or cut resistance undergloves. Water resistance gloves (reusable or disposable) are used on top of the undergloves.

Workers described important properties or needs for development of the hand protection:

- Moisture evaporation (sweating of hands)
- Not too thick to maintain finger dexterity
- Protection against contact cooling
- Warmer sensation of the cut resistance undergloves
- High hygienic demands (washing in minimum of 60°C)

Some of the workers uses two pairs of undergloves (cotton or acrylic) one on the other to prevent contact cooling. Some workers considered two under layers to be too thick and thus hindering finger dexterity.

Heated gloves were not used due to high hygienic and resistance demands. However, heated pipes for warming of hands were installed to some work locations, but their usability during the work process was not sufficient. Improved solutions for warming and rewarming of hands and fingers should be developed.

1.3 Individual cooling of hands

1.3.1 Subjects

Altogether 18 subjects (6 males and 12 females) participated in the study. All the subjects were healthy and free from musculoskeletal disabilities on the upper extremities. Their anthropometric data are shown in Table 1. Length of the hand was measured from the wrist to distal end of middle finger. Circumference of the fingers were measured at the proximal end of each finger.

This study was approved by The Ethical Committee at the Finnish Institute of Occupational Health.

Table 1. The anthropometric data of the subjects.

Item	**Female**	**Male**	**Mean**	**SD**
Number of subjects	12	6	18	18
Age (yrs)	29.7	26.0	28.4	9.7
Height (cm)	166.6	178.1	170.4	10.0
Weight (kg)	61.3	76.4	66.3	11.4
Hand length (cm)	17.23	18.75	17.73	1.17
Middle finger length	7.43	8.13	7.66	0.56
Circumference (mm)				
palm	19.41	21.87	20.23	1.51
index finger	5.94	6.55	6.14	0.47
middle finger	5.88	6.37	6.04	0.44
ring finger	5.48	5.97	5.64	0.43
little finger	4.93	5.47	5.11	0.41
thumb	5.93	6.50	6.12	0.44

1.3.2 Experimental design

The experiments were performed in the climate chamber set to -10 °C (± 2.0 °C). All the subjects participated in the passive cooling measurements. They were exposed to -10 °C in standing position for 60 min. They were dressed to appropriate winter clothing for the exposure temperature. They were wearing a pair of experimental gloves (prototype H1). Skin temperatures were measured by thermistors (YSI 427, Yellow Springs Inc., Co, USA) placed on the dorsal proximal phalanx of the index, ring and little finger and on the dorsal side of the hand. Right hand was used (all the subjects were right handed). Skin temperature data were recorded and saved into the data logger (SmartReaderPlus8, ACR Systems, Canada) in 10 seconds intervals. The subjects were not allowed to move their fingers or hand. Perceived thermal sensation of the whole body, hands and fingers was asked in 10 min intervals using standardizes scale (ISO 10551, 1995). If any of the finger temperature decreased below 10 °C or the subject wanted to leave the climatic chamber, the experiment was terminated. After the measurement, cooling time for index, ring and little finger was calculated from the beginning of the measurement to the time point where finger temperature reached 17 °C. Cooling rate was then calculated as the ratio of finger temperature change during cooling and finger cooling time.

1.3.3 Results and discussion

Skin temperatures of index and little finger and back of the hand during passive cooling measurement are shown in Figures 2-4. For six of the test subjects, experiment was stopped before 60 minutes due to subject’s choice or due to reaching the critical temperature of fingers. Inter-individual variation in finger skin temperatures during the experiment was high. In addition, three diverse types of cooling were identified among the test subjects. Cooling patterns were named as fast, moderate and slow cooling. Majority (11) of the test subjects belonged to the group of fast finger cooling while slow cooling was observed only from two subjects. Number of moderately cooling test subjects was five.

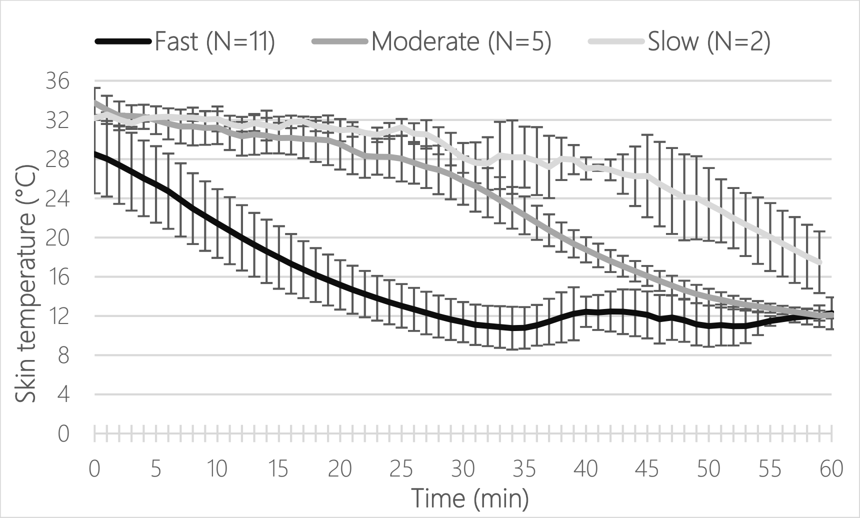

Figure 2. Skin temperatures (mean ± SD) of index finger during passive cooling measurement. Six of the subjects stopped before the 60 min.

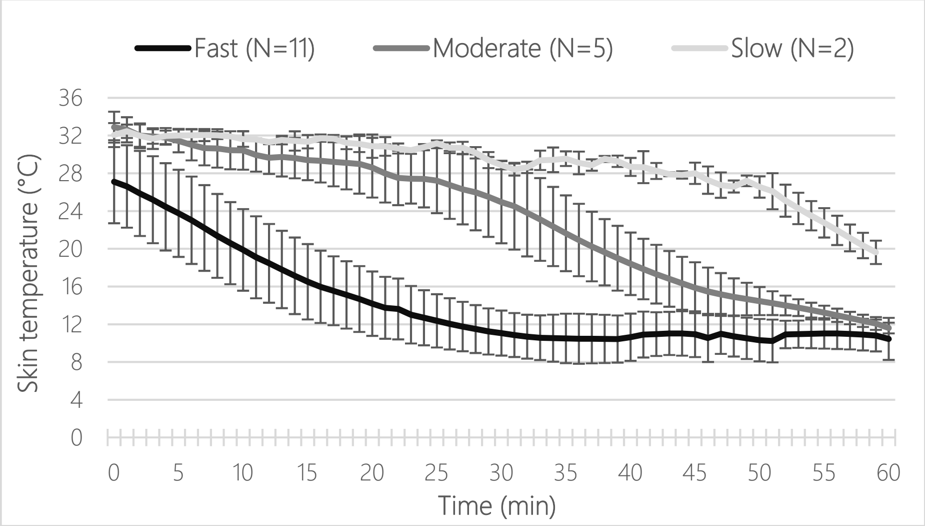

Figure 3. Skin temperatures (mean ± SD) of little finger during passive cooling measurement. Six of the subjects stopped before the 60 min.

Separate cooling patterns were not found from the skin temperature data of back of the hand during passive cooling (Figure 4). However, among the subjects of different cooling groups, slight differences were observed in the change of skin temperature of back of the hand during the measurement. In those subjects who were from the fast finger cooling group, skin temperature of back of the hand decreased on average 8.72 ± 2.14 °C during the measurement while for the subjects of moderate cooling group, the decline in skin temperature of back of the hand was 8.02 ± 1.33 °C and for subjects of slow cooling group, 5.80 ± 0.42 °C. Skin temperature of back of the hand decreased 8.20 ± 2.00 °C on average in all the test subjects during the measurement of passive cooling.

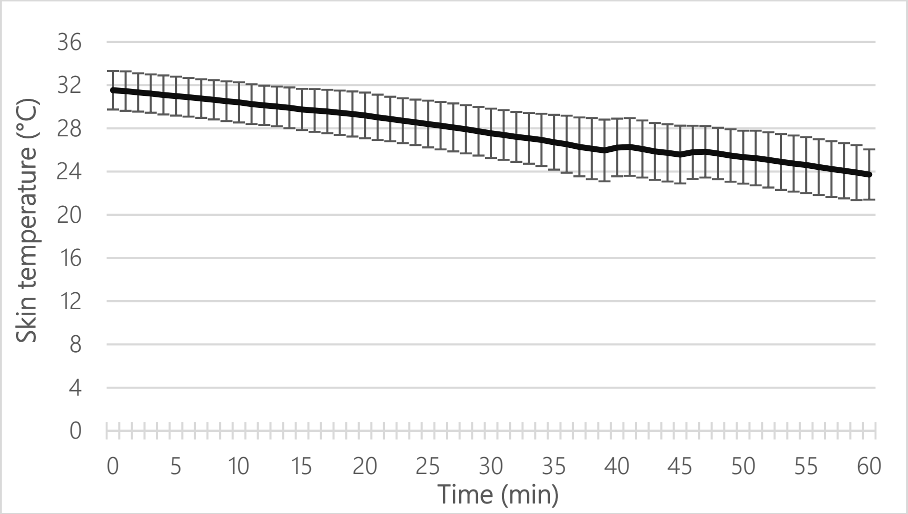

Figure 4. Skin temperatures (mean ± SD) of back of the hand during passive cooling measurement (n=18).

In this study the temperature limit of fingers was chosen to be 17 °C. Cooling times and rates for index, ring and little finger are shown in Table 2. Despite a cooling pattern, finger cooling down to 17 °C occurred in less time than an hour in all the test subjects except in one from the group of slow cooling (Table 2). In moderate and fast cooling groups the cooling time was 27 and 40 min longer, respectively than in the fast cooling group.

*Table 2. Cooling time and rate (mean ± SD) for index, ring and little finger. (*Two subjects belonged to this group but only for the other one, finger skin temperature reached 17°C during cooling. **Only one subject belonged to this group. ***No subjects belonged to this group. ****Two subjects belonged to this group but finger skin temperature did not reach 17°C in either of them).*

		Cooling time (min)			Cooling rate (°C/min)		
Cooling pattern	n	Fast	Moderate	Slow	Fast	Moderate	Slow
Index finger	18	16.1±5.0	43.0±2.0	56.0*	0.7±0.1	0.4±0.04	0.3*
Ring finger	6	14.7±4.8	48.7**	-***	0.62±0.2	0.3**	-***
Little finger	18	14.3±6.6	42.3±5.7	-****	0.7±0.2	0.4±0.05	-****

Average thermal sensation of the fingers during the cold exposure is shown in the Figure 5. Those two subjects who belonged to slow cooling group had thermal sensation neutral until 30 min and after that slightly cool and at the end cool sensation.

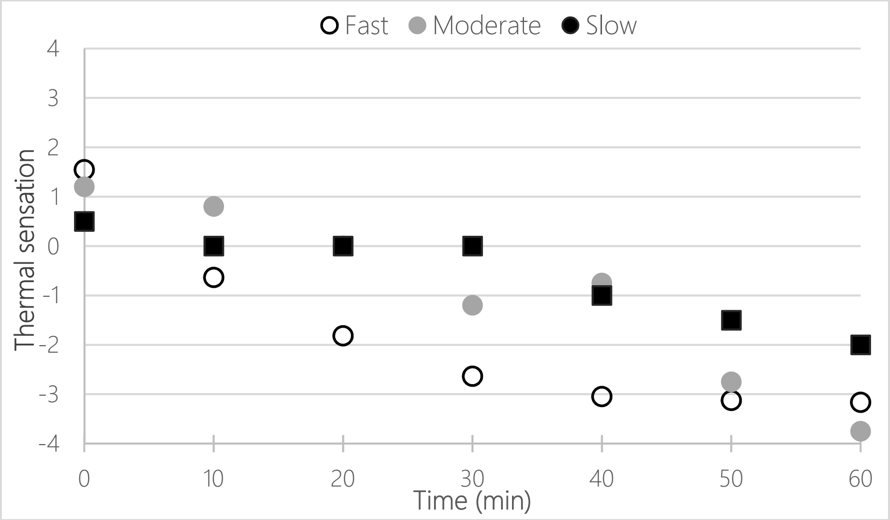

Figure 5. Thermal sensation of the fingers of right hand during measurement of passive cooling separately for fast (n=11), moderate (n=5) and slow groups (n=2). -4 (very cold), -3 (cold), -2 (cool), -1 (slightly cool), 0 (neutral), 1 (slightly warm), 2 (warm), 3 (hot) and 4 (very hot).

The variation of finger skin temperatures at a particular thermal sensation was wide (Figure 6).

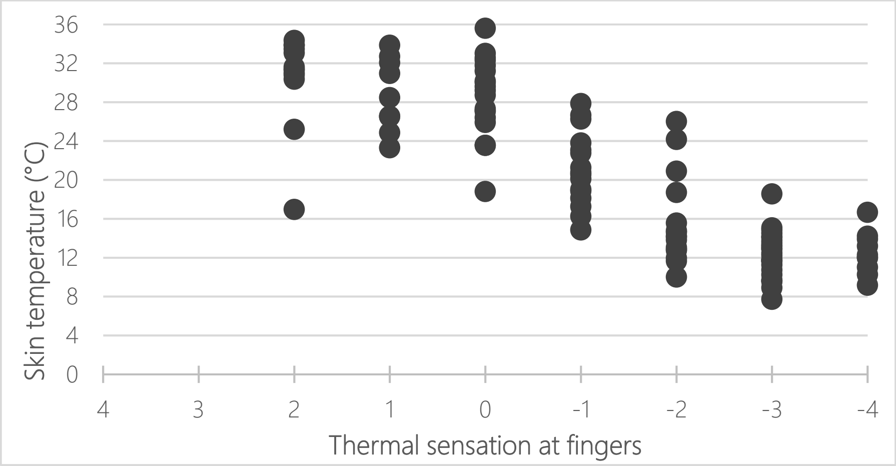

Figure 6. Subjects perceived thermal sensation of the fingers of right hand and skin temperature of index finger during passive cooling (n=18).

Finger cooling results in pain, numbness and loss of effective function. Physical tasks during working may slow down the finger cooling through metabolic heat production, but to maintain optimal finger temperature (that is crucial for effective manual performance) special smart solutions are needed if working in the cold lasts for several hours.

1.3.4 Conclusions

Three cooling patterns were observed. For the fast cooling pattern it was typical that cooling started from the very beginning of the cold exposure. For the moderate cooling pattern, the cooling rate was slow until 30 min and then started to cool faster. Third pattern was slow cooling, where faster cooling started after 40 min of the cold exposure.

Cooling times to reach finger temperature of 17 °C were 27 and 40 min faster for the fast cooling subjects than for the moderate and slow cooling subjects, respectively. According to the literature the finger dexterity is significantly reduced when skin temperature of fingers decreases below 13 °C (e.g. Daanen 2009, Rissanen et al. 2001). If the cooling rate is slow, reduction may be seen already at the finger temperature below 19 °C (Lockhart et al. 1975). In this study the temperature limit for fingers was chosen to be 17 °C although the finger dexterity may not be significantly impaired. This temperature limit was later used as heating set point for the heated gloves.

TASK 2 DEVELOPMENT OF GLOVE PROTOTYPES

In this task the aim was to find optimum solutions for placement and distribution of thermal insulation in a glove in order to have sufficient passive thermal insulation and maintain dexterity of the finger as good as possible. Production of the prototype gloves was outsourced to a glove manufacturer B. Huhta from Kokkola, Finland.

2.1 Development process of the glove prototypes

Development process of the unheated glove prototypes is illustrated in the Figure 7. The results of the Task 1 was used as a base in determining requirements of gloves. In the project co-operative work with the glove manufacture as well as the project partner was done in meetings face-to-face and via emails. 1st prototypes were produced and pilot testing (finger dexterity) were performed to find out functionality of the gloves. Based on the pilot tests some modification was performed to 2nd prototypes that were used in final measurements.

Figure 7. Development process of the unheated glove prototypes.

2.2 Developed glove prototypes

Three different glove prototypes were decided to produce (Figure 8): H1) already existing product by B. Huhta (Falcon), H2) added insulation padding on the back of hand side of the glove, and H3) added insulation padding on glove's both sides equally. Outer material of the 1st prototypes was leather of wild reindeer, weaved liner and semipermeable membrane in between.

Figure 8. Develop prototypes of the unheated gloves: H1) Already existing product by B. Huhta (Falcon), H2) Added insulation padding on back side of the glove, and H3) Added insulation padding on glove's both sides equally

The 1st prototypes were experienced to be too clumsy and therefore modification was done. In the 2nd prototypes the membrane was left out and knitted liner was used. Knitted liner was considered to influence less finger dexterity because there are no seams in the liner. The final (2nd) prototypes were used in the material and physiological measurements. The leather outer glove without liner was used over the heated undergloves.

More commitment and intensive cooperation would be needed with the glove manufacturer to improve finger dexterity properties even further, e.g. by pattern and material modification and development.

TASK 3 INTEGRATING SMART HEATING SYSTEM

In the task it was aimed to integrate smart heating system into those parts of hand wear, which cannot be insulated properly; especially on palmar side of fingers. The smart heating system was planned to consist of units for temperature measurement, control, and heating. The objective was to provide optimal heating to required parts of the hand. Thus the system was expected to enable good manual performance, save energy of the battery of the heating system and provide longer working time. Feedback and ideas for further development was given by project partner SINTEF.

3.1 Carbon fibre heating elements

Carbon fibre tape (specifications in the Table 3) was purchased to be used as heating element in the SmartPro-prototype heated glove. The carbon fibre tape was fixed to the cotton underglove (Figure 9). All fingers were surrounded by the heated tape (105 cm per glove). The leather outer glove without liner was used over the underglove.

Table 3. Specifications of carbon fibre tape heating.

Specifications	
Material	Carbon fibre 100%
Resistance	18±2 Ohm/m
Weight	5±0.5 g/m
Width	17±2 mm
Thickness	0.6±0.1 mm
Tensile strength	50±10 kg

Figure 9. Carbon fibre elements attached into underglove.

Thermostat temperature controller was purchased for the prototype heated glove (1PCS W1209 DC 12V temperature controller) (Figure 10).

Figure 10. Temperature controller of the heated underglove.

Several pilot tests were performed to determine the ideal thermistor size, sufficient power input, upper and lower limit skin temperatures and location of the thermistor. Thermistor included to the controller was too big (2 cm long) and too slow to be able to adjust the finger temperature. Thermistor was changed to smaller and faster responding thermistor.

After several testing upper and lower limit temperatures were adjusted to 28 and 26 °C, respectively. Fingers are cooling and rewarming in different rate of changes. Index finger as a controller finger was most often too cold thus letting the other fingers to warm too much (Figure 11). Middle finger temperature and ring fingers are “central fingers” and could be used as the controller finger for the temperature, but then index and little fingers may remain slightly cool for some individuals (Figure 12). Nevertheless, ring finger temperature was chosen to be the reference and controller temperature for the heating device. Heating power was adjusted to be 10 W.

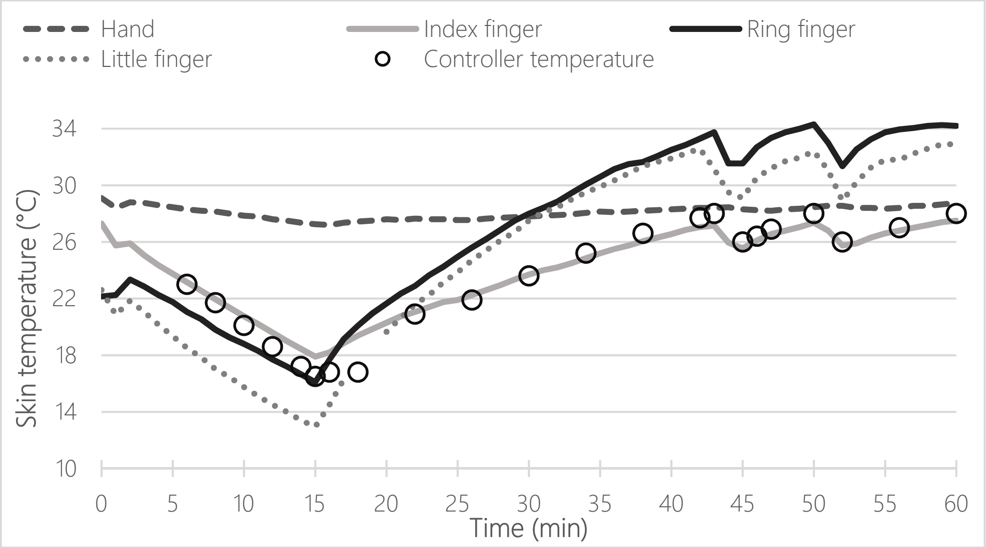

Figure 11. Skin temperatures of hand and fingers. Temperatures controller's thermistor was located to the index finger (indicated by dots). Upper and lower limit temperatures were 28 and 26 °C, respectively. Exposure to -10°C.

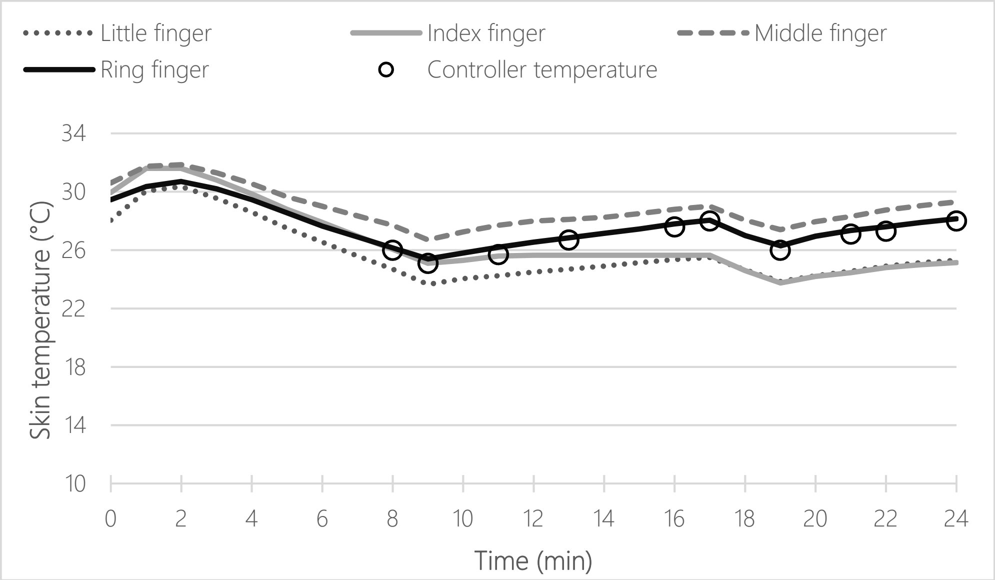

Figure 12. Skin temperatures of hand and fingers. Temperatures controller's thermistor was located to ring finger (dots). Upper and lower limit temperatures were 28 and 26 °C, respectively. Exposure to -10°C.

3.2 Commercial reference glove

For a reference heating system commercial product was purchased from the market. It was produced by NeverCold (Figure 13). The heated glove was selected to correspond with SmartPro-prototype by having thin material (Polyester) integrated with carbon fibre wire heating elements on finger sides. The reference gloves were used under the leather outer glove without liner.

Heating of the commercial gloves is adjusted manually by 3 level battery control system. Temperature of the heating elements is 55 °C (full power), 45 °C (half power) and 38 °C (low power).

Figure 13. Commercial heated reference glove available from the market (Picture: www.nevercold.net).

3.3 Far InfraRed-heating elements

The far infrared (FIR) heating method is based on the longer wavelengths than ordinary infrared (IR) heaters. It is believed that the heating effect of FIR heaters extends deeper inside the tissue than ordinary IR heaters. This technology (Figure 14) was used to study warming of wrist and its effect on finger temperatures. Battery output power was 15 W, heat gain was 200 W/m^2, heating area was about 100 cm^2, and net heating power about 2 W.

Figure 14. FIR heating element.

TASK 4 MATERIAL AND PHYSIOLOGICAL TESTING

This task included measurements of total and local heat transfer as well as material properties of gloves. Measurements of the thermal insulation of the gloves by physiological measurements (skin temperature and heat loss) with test subjects were performed. Measurements of manual performance were performed by standard test protocols and by special task-derived tests. Electromyography (EMG) measurements were also performed with limited test protocol.

4.1 Thermal insulation of unheated prototype gloves

4.1.1 Experimental design

Resultant thermal insulation of gloves were measured based on standard EN 511 (2006) using a thermal hand model consisting eight separate zones. Measurements were performed in climatic room where ambient temperature was adjusted to +10°C, wind speeds 0.3 and 4.0 m/s, and relative humidity 50%. Size of the measured gloves was 10. The resultant thermal insulation, I (m^2K/W), of the gloves was calculated by using equation:

$I = (T_{Hand} – T_A) / Q_{Hand}$

Where T_{Hand} is the mean surface temperature of the measured segment of the hand model (°C), T_A is ambient temperature (°C), and Q_{Hand} is the measured power supply (W/m^2).

4.1.2 Results and discussion

The thermal insulation of the measured unheating prototype gloves and separate zones of each fingers, hand and palm are presented in the Table 4. As expected, the thermal insulation was higher when more insulative padding was used. The results show that even the same material layers are used both sides of the glove (palm and hand sides), the thermal insulation was higher on the palm side of the glove. This is related to the natural posture of hand being concave in the palm side and thus also the material layers are piled up, where as on the hand side the material layers are straight and closely together.

Table 4. The total thermal insulation (m^2K/W) of the unheated prototype gloves and separate segments of the hand in ambient temperature +10°C and wind of 0.3 m/s.

				Thermal insulation (m^2K/W)				
Glove	**Total**	**Thumb**	**Index finger**	**Middle finger**	**Ring finger**	**Little finger**	**Palm**	**Back of the hand**
H1	0.195	0.189	0.141	0.188	0.177	0.188	0.229	0.195
H2	0.215	0.196	0.146	0.193	0.185	0.196	0.239	0.242
H3	0.231	0.238	0.149	0.190	0.176	0.195	0.288	0.245

The thermal insulation of the gloves was measured also in windy conditions (4.0 m/s) (Figure 15). Convective cold performance levels (1-4) are determined in the standard EN 511 for cold protective gloves. The protective level of the prototype glove H1 was 1, and H2 and H3 were in level 2. Wind of 4.0 m/s decreased the thermal insulation of H1 by 30%, H2 by 26 % and H3 by 23%.

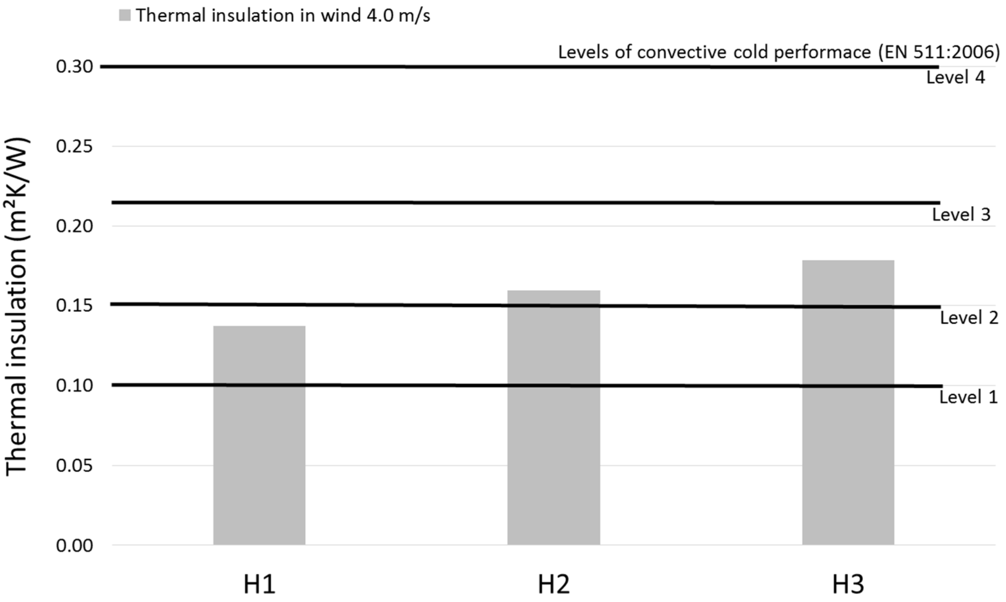

Figure 15. Thermal insulation of the unheating prototype gloves H1-3 in wind of 4.0 m/s at ambient temperature of +10 °C and levels of convective cold performance according to EN 511 (2006).

4.1.3 Conclusions

Thermal insulation of the measured gloves H1, H2 and H2 were 0.195, 0.215 and 0.231 m^2K/W in calm conditions, respectively. Thermal insulation depended on used insulative padding. The results showed, that without additional heating, passive insulation should be added especially on the back of the hand. Moderate wind (4.0 m/s) decreased the thermal insulation of the gloves by 23-30%. The effect of the wind was lower if more insulative padding was used.

4.2 Required additional heating capacity to maintain thermal balance of hands

4.2.1 Experimental design

The thermal hand model (described in the chapter 4.1.1) was used to measure required additional heating power with unheated prototype gloves (H1-3) to maintain hand skin temperature in thermoneutral at ambient temperatures of +10, 0, and -10°C and in wind speeds of 0.3 and 4.0 m/s.

4.2.2 Results and discussion

The required additional heating power was measured in ambient temperatures of +10, 0, and -10°C and in wind speeds of 0.3 and 4.0 m/s and estimated in colder ambient conditions as illustrated in Figure 16.

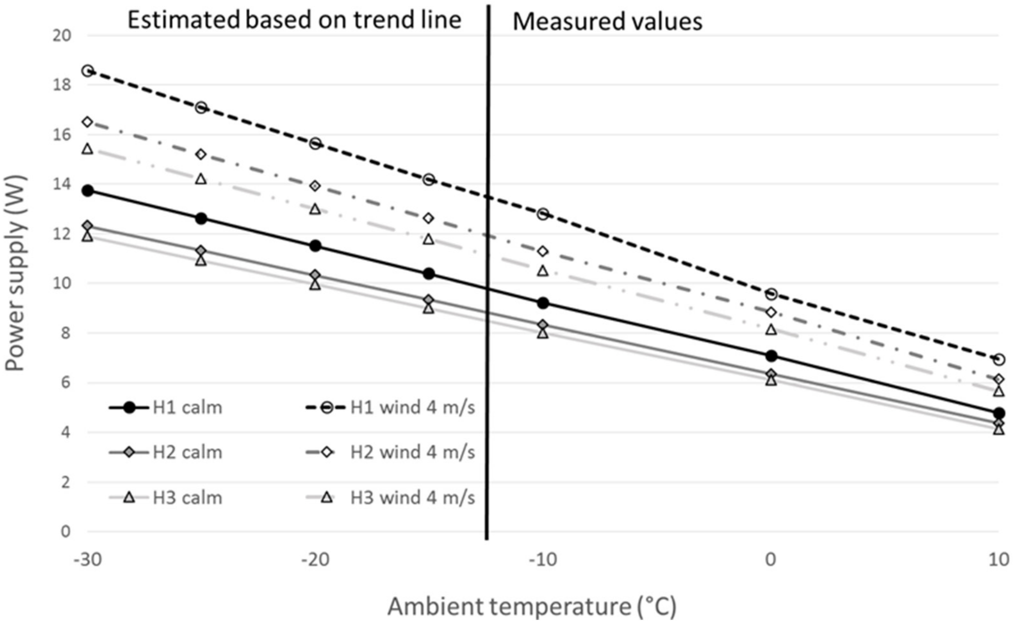

Figure 16. The measured and estimated additional power supply (W) of the prototype gloves H1-3 to maintain hand surface temperature at constant.

4.2.3 Conclusions

The results indicated that in ambient temperature of -10°C additional heating power should be 8-9W in calm conditions (0.3 m/s) and 11-13W in moderate wind (4.0 m/s) with the measured gloves.

4.3 Manual and finger dexterity

4.3.1 Experimental design

Nine subjects (3 males, 6 females) from the passive cooling group participated in measurements of manual performance. Measurements included four different manual tasks: Minnesota Hand Dexterity Test, key grip force (Newtest, Finland), hand tool dexterity test (Bennet Dexterity Test), and dexterity test according to EN 420. Each test subject performed all the tasks with bare hands, with the three produced unheated prototype-gloves (H1-3), with commercial reference glove and with SmartPro prototype-gloves. The reference and the SmartPro undergloves were covered by the leather outer glove without liner. Two trial rounds were given before each test for practice. Measurements were performed at room temperature.

In Minnesota Pegboard (Figure 17), subjects turned twelve consecutive pegs 180° as quickly as they could. Time was taken down.

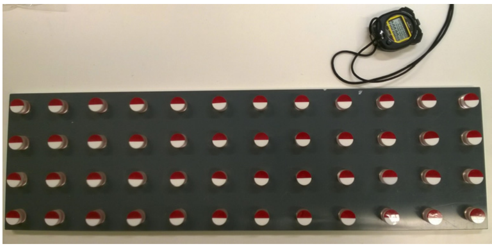

Figure 17. Minnesota Pegboard test.

In the key grip force test (Figure 18) the subjects turned maximally the button by the thumb and two fingers. Average force (in grams) from the three trials was calculated.

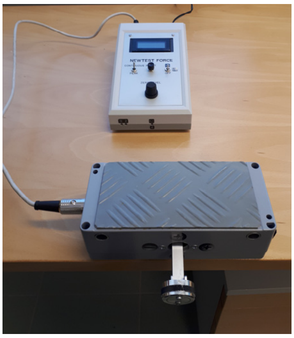

Figure 18. Key grip force test.

The gross motor test was performed by the Bennet Dexterity test (Figure 19). Three different sizes of bolts, nuts and washers were dismounted by using a wrench, an appropriate size of fork wrench and a screwdriver. After dismounting all the pieces (all put in the small box) the subjects started from the biggest bolt, nut and washer and picked up them from the box and mounted them together. All three sets were mounted. Time was taken down. Tactile and finger dexterity was required while picking up small pieces and gross motor function while using the hand tools.

Figure 19. Bennet Dexterity Test is a gross motor test that measures manipulative skills of the hands using medium-sized tools

Tactile sensitivity was tested with dexterity test according to EN 420. Subjects picked up five sticks (Figure 20.) of different diameter (11, 9.5, 8, 6.5 and 5 mm) three times, starting from the thickest one. It was required that subject had tactile sensation of the stick in his/her fingers.

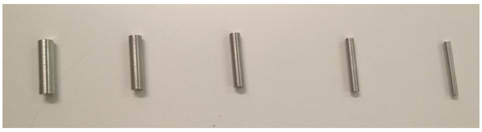

Figure 20. Dexterity test according to EN 420.

4.3.2 Results and discussion

The results of the manual and finger dexterity tests are compiled into Table 5. The best performance was accomplished with SmarPro prototype gloves in Minnesota Pegboard, in hand tool dexterity test and in dexterity test according to EN 420. As for key grip force, the greatest force was achieved with H3-gloves. Conversely, the greatest decrements in performance were observed with H3-gloves in Minnesota Pegboard and in hand tool dexterity test, and with commercial gloves in key grip force and in dexterity test according to EN 420.

Table 5. Impairment/improvement in performance in manual tasks with different gloves in comparison with the performance by bare hands (n=9). Table shows the average of individual differences (%) in performance.

	Minnesota Pegboard	**Hand tool dexterity test**	**Dexterity test (EN 420)**	**Key grip force**
	Impairment (%)	Impairment (%)	Impairment (%)	Improvement (%)
H1	41.6	36.6	24.4	38.6
H2	35.9	39.4	26.7	38.4
H3	51.7	49.3	20.0	**39.2**
Commercial	42.4	53.2	28.9	31.6
SmartPro prototype	**23.4**	**32.8**	**6.7**	36.3

4.3.3 Conclusions

SmartPro prototype glove showed smallest impairment in relation to bare hand performance than the other gloves. H3 glove was the thickest glove and provided the best friction needed for the key grip force. Tip of the fingers in gloves H1-H3 and commercial reference glove were not ideally designed causing impairment in finger dexterity test.

4.4 Physical strain caused by gloves

In different occupations physical strain of the working muscles is conventionally measured with electromyography (Oksa et al. 2014). The use of electromyography is a useful, reliable and sensitive tool for differentiating the strain induced for the muscles in varying conditions.

4.4.1 Subjects

Two female subjects accustomed to Minnesota pegboard and dexterity tests (EN 420) performed the tests.

4.4.2 Experimental design

The subjects were asked to perform both tests as fast as possible and the use of different gloves (H1-H3) during the tests were randomised. During the tests EMG activity of the wrist flexor (*m. flexor carpi radialis*) and extensor (*m. extensor carpi radialis*) muscles were measured (ME6000, Oulu, Finland) with bipolar surface electrodes. The electrodes were placed on the belly of the muscle with interelectrode distance of 2 cm and the ground electrode was placed above inactive tissue. The acquired signal was preamplified 1000 times and averaged (aEMG) with 100 ms time frame. The results are expressed as microvolts (µV).

4.4.3 Results and discussion

Tables 6 and 7 show the average EMG activity (aEMG) of the wrist extensor and flexor muscles during the tests.

The condition "without gloves" shows the least EMG activity, therefore the strain to the working muscles is the lowest. While using different gloves the strain increases but no marked difference in the strain between them was found.

Table 6. aEMG (µV) while performing Minnesota Pegboard.

	Subject 1		**Subject 2**	
	Extensor	**Flexor**	**Extensor**	**Flexor**
Without gloves	97	34	128	39
H1	129	50	200	76
H2	109	43	168	69
H3	105	45	154	62

Table 7. aEMG (µV) while performing dexterity test according to EN 420.

	Subject 1		**Subject 2**	
	Extensor	**Flexor**	**Extensor**	**Flexor**
Without gloves	29	11	45	16
H1	56	26	83	62
H2	55	25	87	65
H3	64	33	103	66

4.4.4 Conclusions

In this pilot experiment no marked difference in the strain of wrist extensor/flexor muscles was found while using different gloves. This may have partly been due to relatively short exercise time. Based on these results the further use of EMG measurements in the project was rejected.

4.5 Pilot testing of wrist and arm heating

Basically fingers could be maintained comfort (22-25 °C) by applying heat to torso during a cold exposure. The torso has to be heated up to 42 °C before the effect can be seen in the fingers (eg., Brajkovic et al. 1998). In general, auxiliary heating is integrated to the gloves where the heat is applied directly to fingers and hand.

Warming of wrist/palm area has been shown to increase finger temperatures and blood flow in distal parts of the hand (Koscheyev et al. 2001). In their study liquid warming system was used and the water temperature was warmed up to 45°C. Castellani et al (2017) showed that direct heating applied to forearm and face reduced the decline in fine and gross manual dexterity by 20-50% at 0°C. Heating temperature set point was 42 °C which resulted in forearm skin temperature of 38.5 °C. However, finger temperature of bare hand decreased to 11.6 °C. Without any heating finger skin temperature was 10.9 °C.

In this SmartPro project we conducted some pilot studies using wrist or forearm heating by different heating methods which will be described below.

4.5.1 Heating of hand and wrist by FIR heating pad

FIR heating pads were used to apply heating to the back of hand and to the wrist (Figure 21). Skin temperature of fingers, back of hand and wrist were measured (Figure 21). Heat flux was measured from wrist and back of the hand. Protective glove was used together with the heating pad. Measurements were performed at -10°C and the subjects were standing during the exposure.

Figure 21. FIR heating pads for hand and wrist (upper panel), proterctive glove above the pads (lower left) and location of thermistors and heat flux transducers (lower right).

Finger temperature continued cooling although the heating was applied to the back of the hand (Figure 22). Wrist heating induced wrist warming but no effects were seen in the fingers (Figure 22).

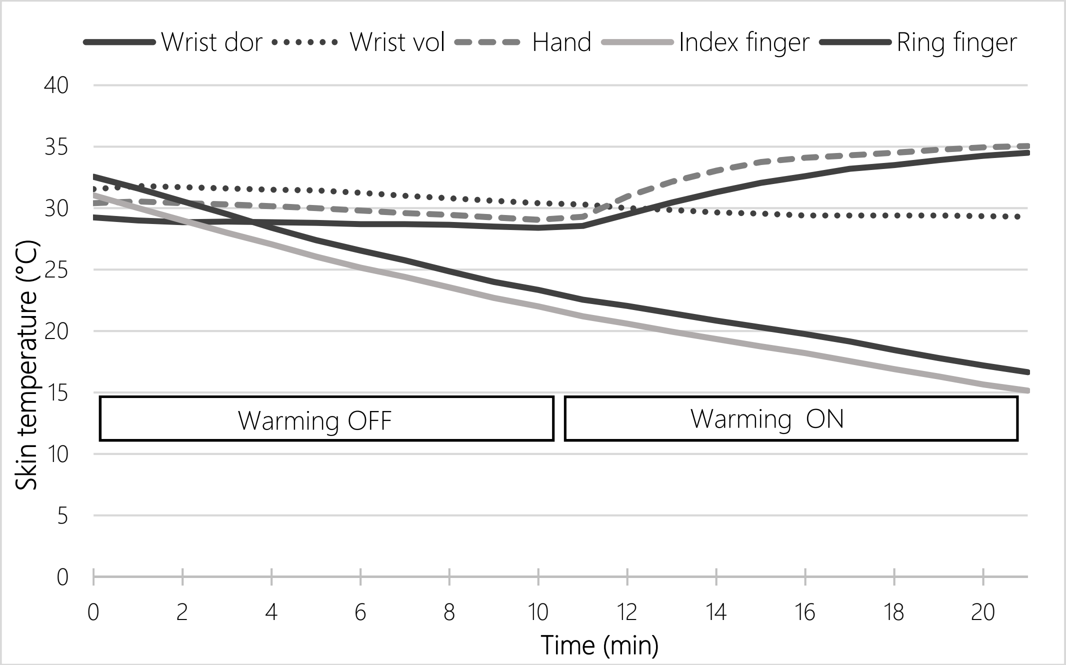

Figure 22. Skin temperatures of index and ring fingers, of back of the hand, of wrist (dorsal and volar) during the exposure to -10 °C. Heating was applied to hand and wrist after 10 min from the beginning

Heat flux measurements show that heat gain was approximately 200 W/m^2 while the wrist and hand warming was on (Figure 23). Heating pad covered appr. 100 cm^2 of the hand and forearm resulting in net heating power only approximately 2 W. Battery output power was 15 W. Hand and wrist temperatures was in maximum 35 °C which was probably too low to induce finger warming.

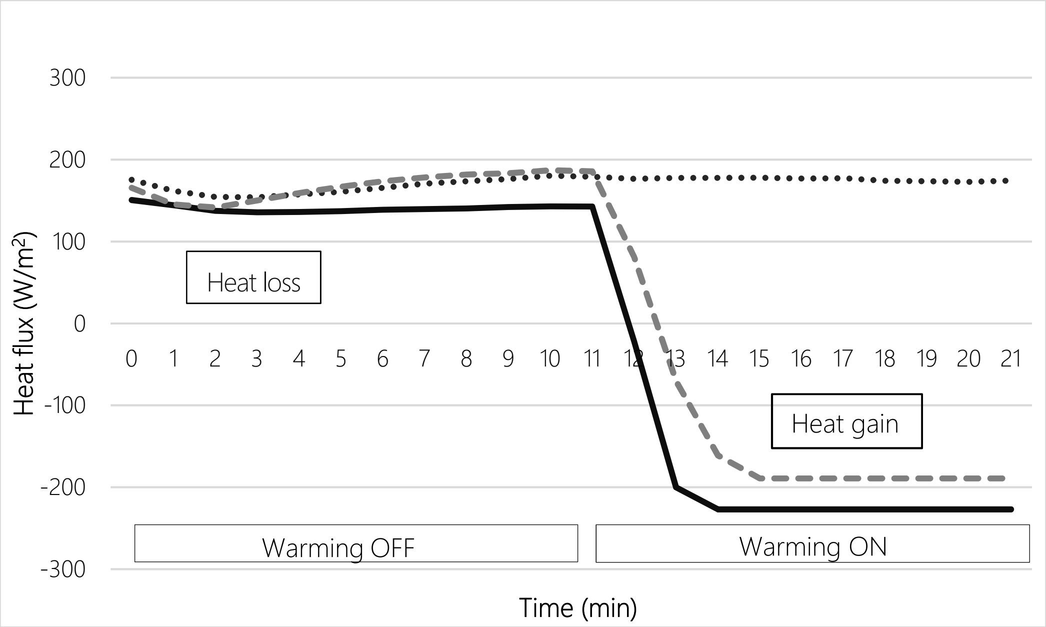

Figure 23. Heat flux at wrist (dorsal and volar) and at back of the hand. Heat loss occurred during no heating and heat gain while heating was applied.

4.5.2 Heating of hand and wrist by carbon fibre rope

Hand and wrist heating was also tested by using carbon fibre rope. Tape was sewed onto the cotton underglove (back of the hand and wrist) (Figure 24). Heating power input was approximately 10W. The underglove was covered with the leather outer glove without liner.

Figure 24. Hand and wrist heating by carbon fibre rope.

Skin temperature of the back of the hand and volar side of the wrist as well as of fingers were measured from both hands. Right hand had the heating system and left hand was without heating. Similar underglove and overglove were used in both hands. Heating system increased the right hand and wrist skin temperatures while left hand and wrist were not affected during the exposure to 10 °C (Figure 25).

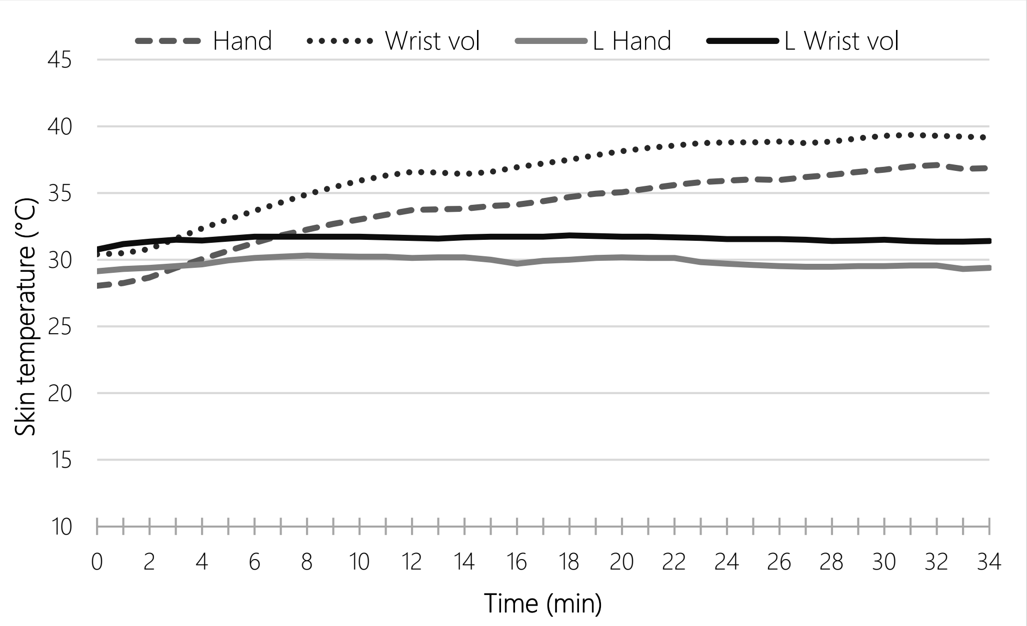

Figure 25. Skin temperatures of back of the hand (heating, Hand) and unheated (L Hand) and of wrists (Wrist heated, L Wrist unheated) during the exposure to 10 °C.

Skin temperature of fingers decreased in spite of the heating applied to the right hand (Figure 26). No difference could be seen between the heated and unheated hand.

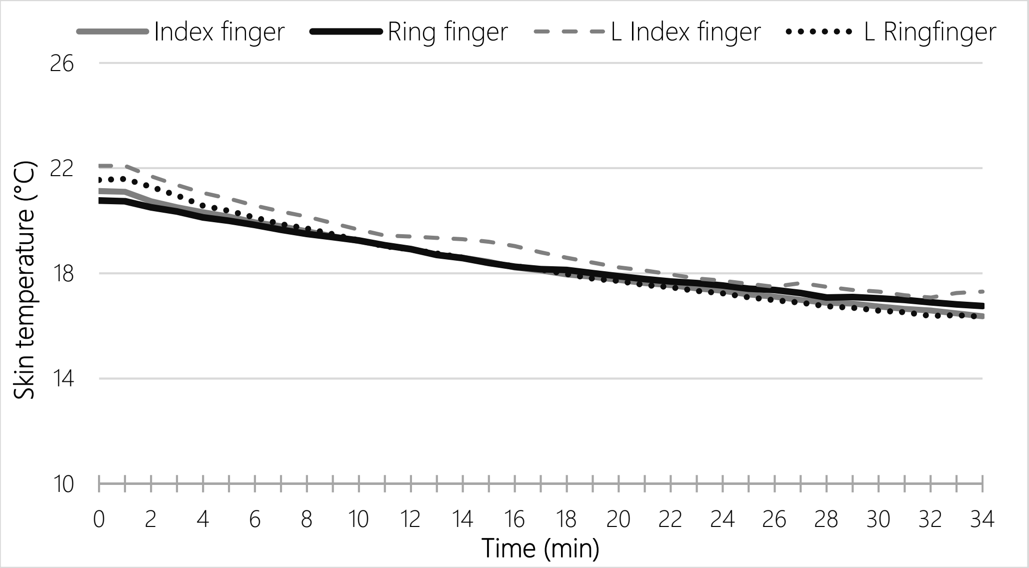

Figure 26. Skin temperatures of fingers during heating and without heating (L) at 10 °C.

4.5.3 Heating of forearm

Carbon fibre tape was used to apply heat on the forearm. Heating of forearm up to 38 - 40 °C required heating of the tape up to 54 °C. Due to the risks of pain and burning of the skin this experiment was withdrawn from the study.

4.5.4 Conclusions

Heating of wrist and back of the hand or forearm by the carbon fibre could not warm or even prevent cooling of the fingers. In the study of Castellani et al (2017) the finger temperature was also low (11.6 °C) even though the forearm was heated up to 38.5 °C. Further research with different heating systems or solutions is needed.

TASK 5 VALIDATION OF GLOVE HEATING SYSTEMS

Solutions for simple (optimized thermal insulation) and comprehensive (smart active heating) handwear was tested and further developed on the basis of their usability and effectiveness.

5.1 Heating of fingers by SmartPro prototype

5.1.1 Experimental design

Nine fast cooling subjects (2 males, 7 females) were chosen from the passive heating group. They participated in the experiment in which they were wearing the SmartPro prototype heating glove at ambient temperature of -10 °C in standing position for 60 min. Over the heated glove was the leather outer glove without liner (Figure 27). Subjects were dressed to appropriate winter clothing. Thermistor of the temperature controller was placed on ring finger. In the temperature controller, upper and lower limits of finger temperature were 26 °C and 28 °C. Heating was turned on when the skin temperature of the finger, on which the thermistor was placed, was declined to approximately 17 °C. This temperature limit value was determined from the passive heating results. When the finger temperature reached 28 °C temperature controller started to adjust the temperature between 26 and 28 °C. Thermal sensations of the whole body, hands and fingers were asked in 10 min intervals using standardized scale.

Figure 27. The SmartPro prototype glove.

5.1.2 Results and discussion

Figure 28 shows the finger warming patterns during cooling to 17 °C and after the heating was turned on. When the finger temperature reached 28 °C temperature controller started to adjust the temperature between 26 and 28 °C very accurately. All the subjects completed the 60-min exposure.

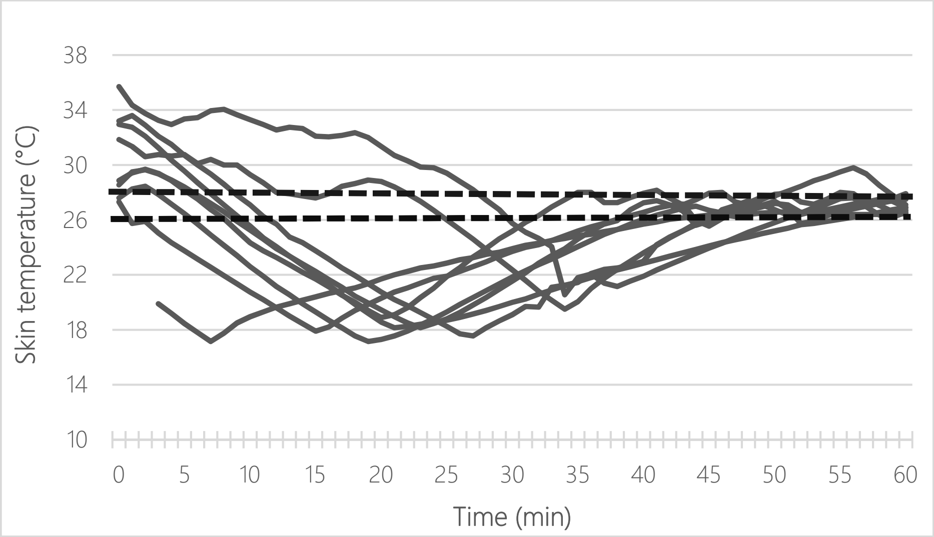

Figure 28. Individual temperature curves of ring fingers with SmartPro prototype (n=9). Thermistor of the temperature controller was placed on ring finger. Heating was turned on when finger skin temperature was declined to approximately 17 °C. Upper and lower limits of temperature were 26 and 28 °C.

Back of the hand was kept warm by the SmarPro prototype glove, because the carbon fibre covered also hand (Figure 29).

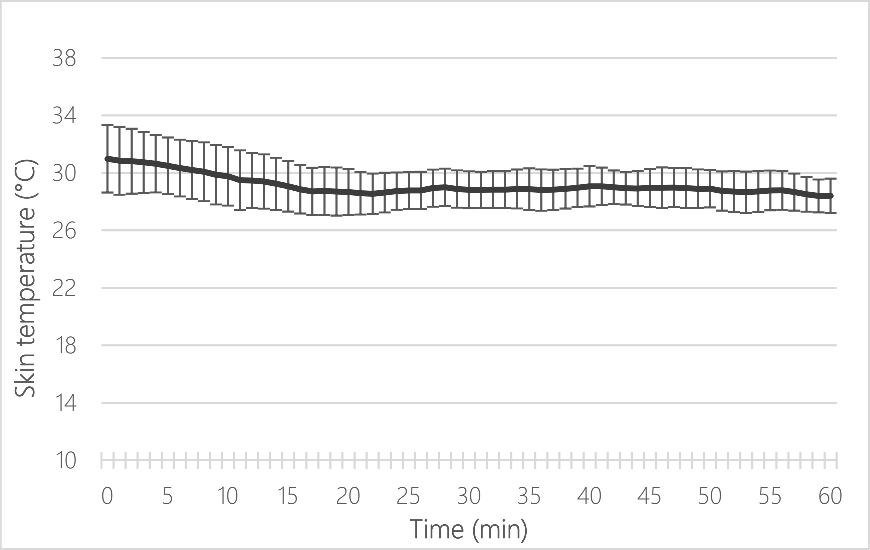

Figure 29. Skin temperatures (mean ± SD) of back of the hand while wearing heating glove prototype at -10°C for 60 min (n=9).

Rewarming time was calculated for fingers from the time point of lowest skin temperature to the time point in which finger skin temperature reached 26 °C. Rewarming rate was then calculated as the ratio of temperature change during rewarming and rewarming time.

Rewarming time and rate for index, ring and little finger are shown in Table 8. Ring and little fingers rewarmed faster than the index finger, which tended to remain below 26 °C.

Table 8. Rewarming time and rate (mean ± SD) for fingers while wearing SmarPro prototype glove at ambient temperature of -10°C for 60 min. n = number of subjects whose finger temperature reached 26 °C.

	n	Rewarming time (min)	Rewarming rate (°C/min)
Ring finger (controller finger)	9	19.87 ± 9.07	0.45 ± 0.15
Index finger	2	28.50 ± 8.49	0.31 ± 0.08
Little finger	7	16.90 ± 9.31	0.83 ± 0.31

Thermal sensation of the fingers followed the cooling and rewarming patterns (Figure 30). For most of the subjects the heating was switched on after 20 min of entering the climatic chamber.

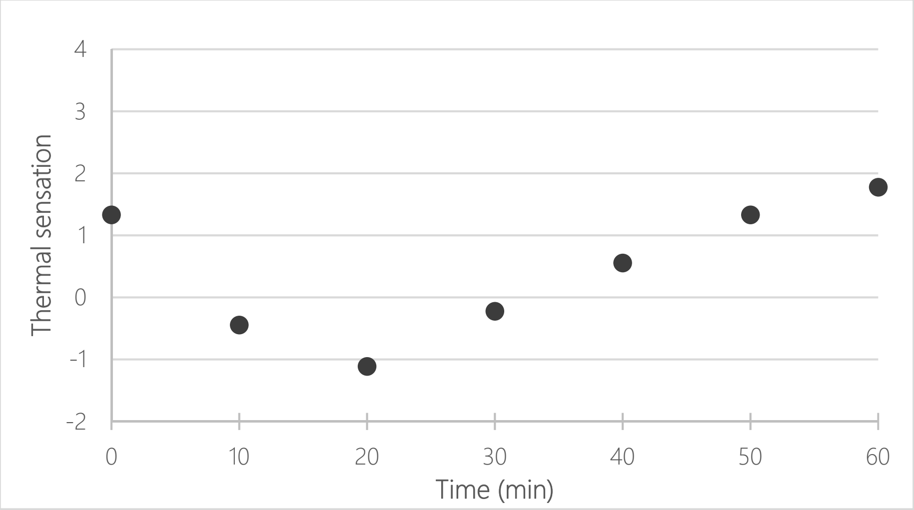

Figure 30. Thermal sensation of the fingers of right hand during measurement in which subjects were exposed to -10°C for 60 min, wearing prototype heating gloves. Heating was turned on when finger skin temperature was approximately 17 °C. (n=9). -4 (very cold), -3 (cold), -2 (cool), -1 (slightly cool), 0 (neutral), 1 (slightly warm), 2 (warm), 3 (hot) and 4 (very hot).

5.1.3 Conclusions

Using the SmartPro prototype glove with the temperature controller the finger temperature where the controller thermistor was situated was very accurately maintained in the required temperature range. Controlling temperature in all the fingers by one controller unit in one finger was challenging. Especially index finger temperature tended to remain too low while the other fingers in the same time warmed above 30 °C. More research is needed to quantify equal heating power to all fingers.

Battery life of the heating system can be extended when the heating is applied only when needed to rewarm hand and fingers.

5.2 Heating of fingers by commercial product

Commercial glove (brand name NeverCold) was used as a reference heating system (Figure 31).

Figure 31. Commercial heating glove covered with the leather outer glove without liner.

5.2.1 Experimental design

Nine fast cooling subjects (3 males, 6 females) were chosen from the passive heating group. They participated in the experiment in which they were exposed to -10°C in standing position for 60 min while wearing a pair of commercial reference heating gloves that are available in the market. In those gloves, temperature can be adjusted to three different levels. Again, subjects were dressed to appropriate winter clothing. Skin temperatures of index, ring and little finger and dorsal side of the hand were measured from right hand and saved into data logger in 10 seconds intervals. Heating was turned on to the warmest level when finger temperature was declined to approximately 17 °C. Thermal sensations of the whole body, hands and fingers were asked in 10 min intervals.

5.2.2 Results and discussion

Skin temperatures of index and ring finger and dorsal side of the hand during exposure are shown in Figures 32-33. Fingers started to rewarm immediately the heating was turned on.

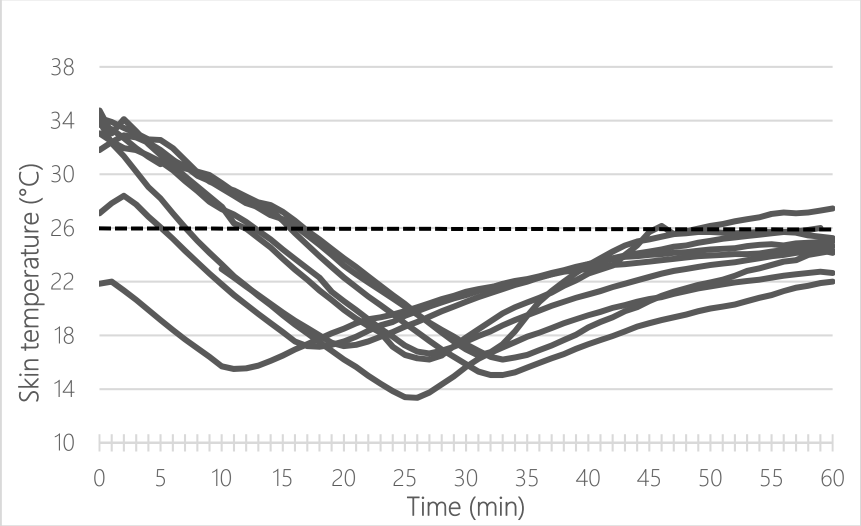

Figure 32. Individual cooling and rewarming curves of index finger while wearing commercial heating glove (n=9).

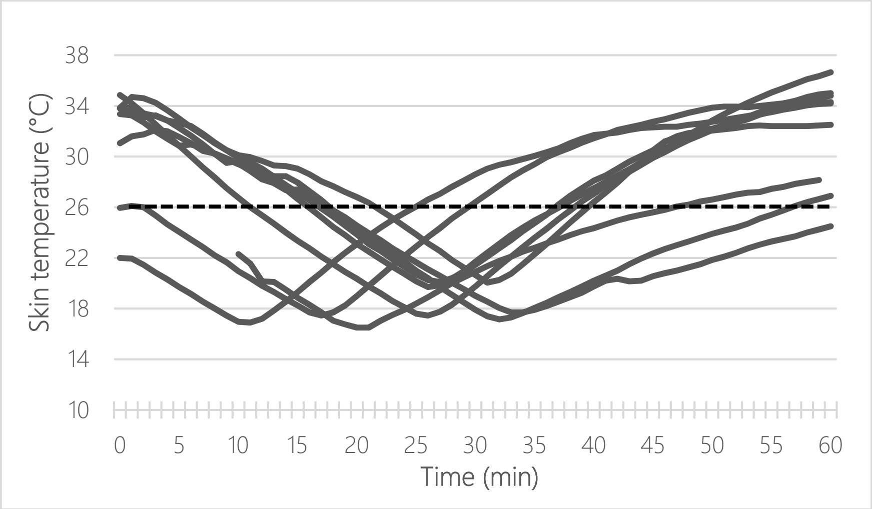

Figure 33. Individual cooling and rewarming curves of ring finger while wearing commercial heating glove (n=9).

Rewarming was not observed in back of the hand (Figure 34). In fact, skin temperature of dorsal side of the hand decreased on average 7.19 ± 1.97 °C during the 60 min exposure to the cold while wearing commercial reference heating gloves.

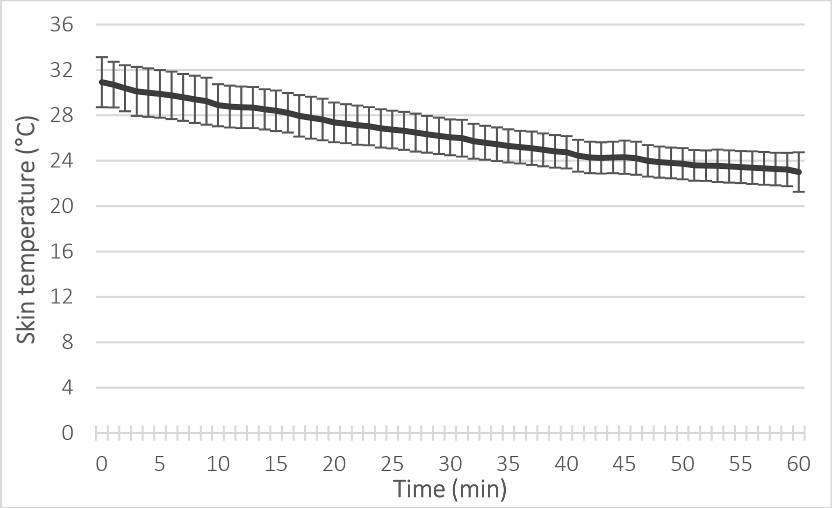

Figure 34. Cooling of back of the hand while wearing commercial heating glove (n=9, mean ± SD).

Rewarming time was calculated for fingers from the time point of lowest skin temperature to the time point in which finger skin temperature reached 26 °C. Rewarming rate was then calculated as the ratio of temperature change during rewarming and rewarming time.

Rewarming time and rate for the three fingers of interest are shown in Table 9. Rewarming was fastest in ring finger, while little and index finger were slower to rewarm.

Table 9. Rewarming time and rate (mean ± SD) while wearing commercial heating glove. n = number of subjects whose finger temperature reached 26 °C.

	n	**Rewarming time (min)**	**Rewarming rate (°C/min)**
Ring finger	7	15.03 ± 6.86	0.58 ± 0.15
Index finger	3	25.07 ± 11.47	0.43 ± 0.17
Little finger	7	19.26 ± 6.49	0.59 ± 0.19

Thermal sensation of the fingers followed the cooling and rewarming patterns (Figure 35). For most of the subjects the heating was switched on after 20 min of entering the climatic chamber.

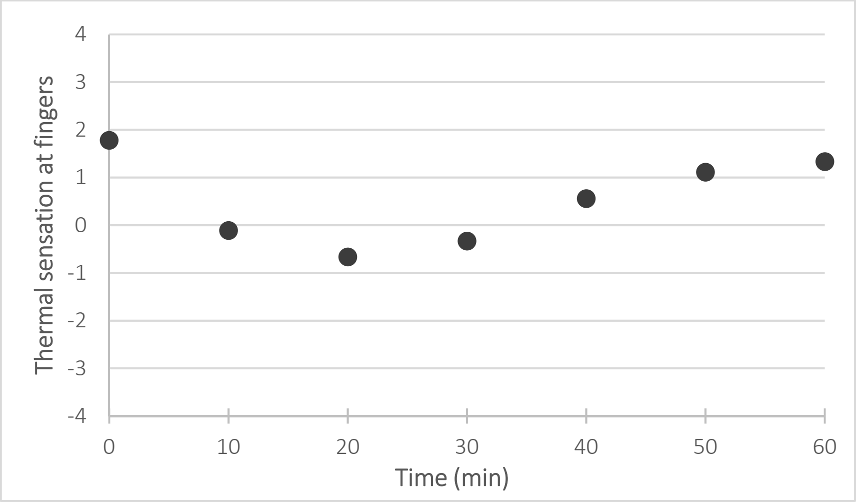

Figure 35. Thermal sensation of the fingers of right hand during measurement in which subjects were exposed to -10°C for 60 min, wearing commercial heating gloves. Heating was turned on when index finger skin temperature was approximately 17 °C. -4 (very cold), -3 (cold), -2 (cool), -1 (slightly cool), 0 (neutral), 1 (slightl

5.2.3 Conclusions

Fingers started to rewarm immediately the heating was applied to the glove. However index finger did not reach the 26 °C during the 60 min exposure except in three subject from the nine. The same phenomenon was seen while using SmartPro prototype.

Back of the hand did not rewarm due to the lack of heating fibre and it was also rated as slightly cool by most of the subjects. Temperature difference was about 3 °C between the two heating gloves.

In the commercial gloves the heating has to be controlled manually, which may cause overheating in the fingers and battery life may be shorter.

Both SmartPro prototype and commercial heating gloves could increase the finger temperature during the heating period compared to unheated situation. Thermal sensations showed similar responses in both heating gloves (Figure 36).

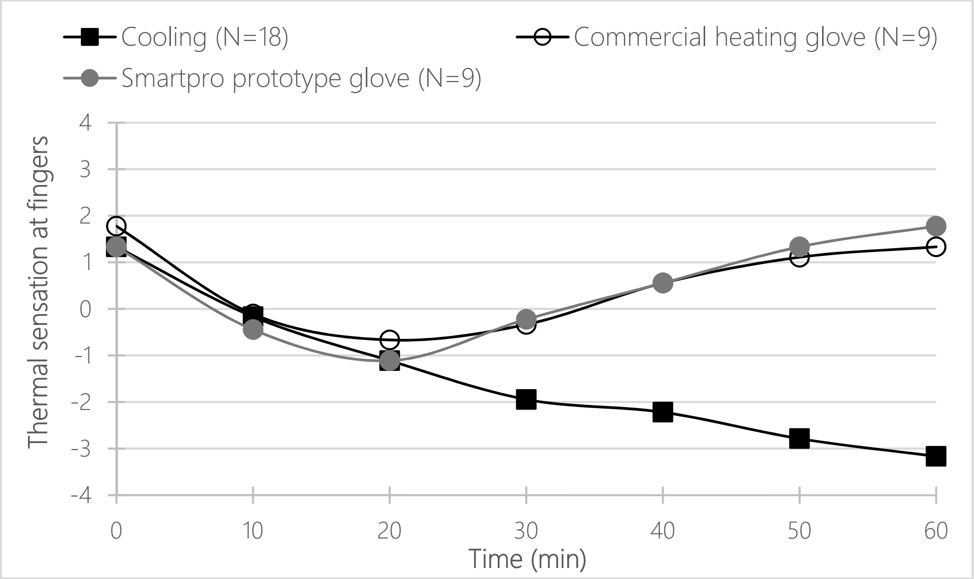

Figure 36. Thermal sensations of the fingers during exposure to -10°C for 1 h, test subjects wearing either H1 gloves, commercial heating gloves or SmartPro prototype gloves. (-4 (very cold), -3 (cold), -2 (cool), -1 (slightly cool), 0 (neutral), 1 (slightly warm), 2 (warm).

CONCLUSIONS

In the Work Package 2 it was developed comprehensive solution that provides smart interactive heating system. The SmartPro interactive handwear was based on new design, sensor and software technology, and wearable auxiliary heating devices. In addition, the development process took into account design of the optimal thermal insulation distribution on the hand.

The SmartPro solution was shown to be the most suitable for workers that have fast or moderately cooling fingers. Figure 37 illustrates SmartPro concept that can be used to evaluate workers' individual sensitivity to cold together with occupational health care personnel.

Prevention of the finger cooling can extent the safe working time in the cold with acceptable thermal responses of the body, and thus, improve work capacity and safety at work. Additional heating of fingers equalize possibilities of individuals to work safely in the cold climate. The solution can be applied to the most type of industries requiring good manual performance in the cold. In addition obtained information is also valuable to the on-going process of the standardization of smart personal protective equipment.

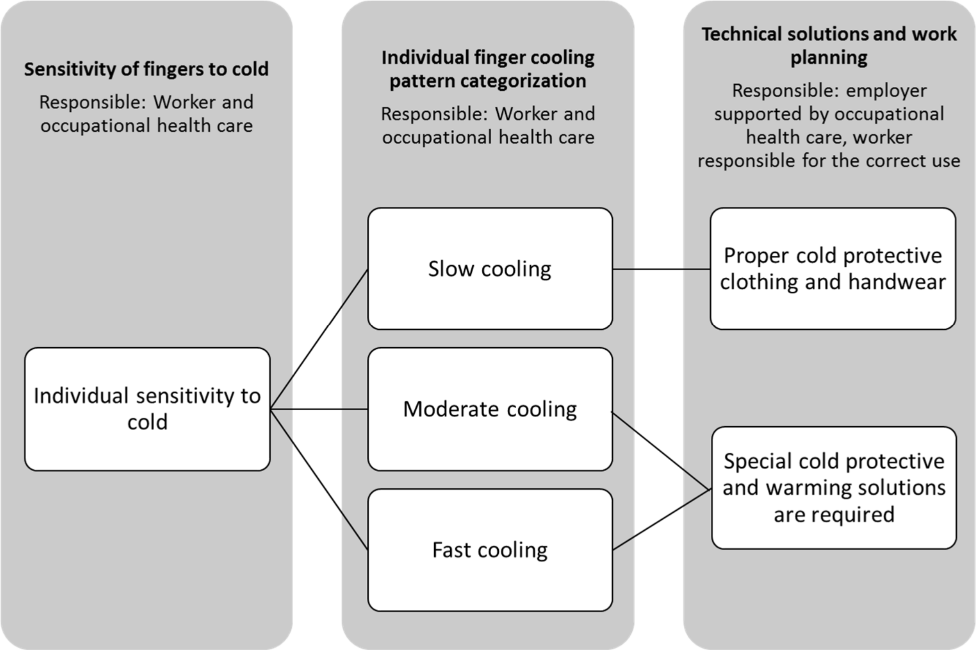

Figure 37. SmartPro concept for evaluating optimum hand protective solutions.

Future perspectives

In the future the system could act as a warning system to detect not only cold temperatures but also high cooling rates and give a wireless alarm if necessary. Development of the batteries has been rapid and it can provide longer using times in the future with lighter and smaller devices. Also sensor technology is developing constantly. This will lead to new sensor solutions e.g. based on printed technology and enabling wireless and continuous monitoring of skin temperatures while working in the cold.

DISSEMINATION OF RESULTS

The dissemination of the results was delivered to stakeholders, such as mining, petroleum, construction, fisheries, through workshops and seminars, as well as other researchers through conferences, workshops, papers and reports. Workshop-type regular meetings between all partners was organized both in situ consisting cooperative working, integration of knowledge from all work packages, and communication with stakeholders.

Meetings, workshops, seminars and education:

- 20-21 August 2015, Project kick-off, Laboratory visit and WorkShop in Oulu. The workshop consisted visit and demonstrations in the FIOH Laboratory of Clothing and Laboratory of Physiology. Facilities of studying, among others, manual dexterity, contact cooling, glove functionality and thermal protection in the cold were demonstrated.
- 15-16 February 2016, 2nd SmartPro WorkShop in Trondheim. WorkShop included demonstration of the SmartPro sensory system and the SINTEF Work Physiology Laboratory SINTEF presented the SmartPro system and preliminary results from the pilot tests.
- 5th September 2016, International Autumn School «Study of human working capacities in the Arctic» in Arkhangelsk, Russia. Smart solutions for industrial work in the Arctic regions was presented and discussed among participants.
- 15-16 November 2016, 3rd Project meeting in situ and workshop in Helsinki. In the workshop was presented and demonstrated testing of PPE in FIOH and visited laboratories of physiology, sleep and quantified employee.
- 15-16 May 2017, NIVA – Human Factors in Arctic Work. Education on manual performance and protection of hands in the cold. Helsinki.
- 7-8 March 2017, SmartPro Project meeting and Workshop in Oslo. Demonstration of the SmartPro sensory system was presented.
- 6 October 2017, Protection of hands against cold (presentation in Finnish). Työ- ja suojavaatetuksen ajankohtaispäivät, Kuopio.
- 27th February 2018, Final meeting and seminar of SmartPro in Trondheim.
- Project results has been disseminated during laboratory visits to hundreds of visitors during the project period.

Symposiums and conferences:

- Jussila K, Rissanen S and Rintamäki H. SmartPro -Project − Smart protective solutions for industrial safety and productivity in the cold. Abstract. PPE2016 – the 13th

European Seminar on Personal Protective Equipment (PPE). Saariselkä, Finland, 26-28th January 2016.

- Jussila K, Wiggen ON, Rissanen S, Mänttäri S, Seeberg TM, Austad HO, Faerevik H and Rintamäki H. Smart protective solutions for industrial safety and productivity in the cold. Abstract. 4th Saf€ra Symposium. Emergence of a New Collaborative Work Programme on Industrial Safety. Athens, Greece. 12-13 April 2016. 17.
- Jussila K, Rissanen S and Rintamäki H. Smart Protective Solutions for Work in the Cold. Injury Prevention. Safety 2016 World Conference, Volume 22, supplement 2, September 2016. A144.
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- Jussila K, Wiggen Ø, Rissanen S, Austad HO, Seeberg TM and Rintamäki H. Smart Protective Solutions for Industrial Safety and Productivity in the Cold – SmartPro. Abstract. 5th Saf€ra symposium. Bilbao, Spain. 18-19 May 2017.
- Jussila K, Rissanen S and Rintamäki H. Heated Gloves for Rewarming and Sustaining Hand Temperatures at Cold Work. Proceedings of 17th International Conference on Environmental Ergonomics, Kobe, Japan, November 2017.
- Wiggen Ø, Seeberg TM, Austad HO, Færevik H. Individual variations in perceived thermal sensation and skin temperature of fingers at different work intensities during cold exposure. Proceedings of 17th International Conference on Environmental Ergonomics, Kobe, Japan, November 2017.
- Jussila K and Rissanen S. Use of Heated Gloves to Prevent Cooling of Finger Temperatures at Cold Work. Abstract. PPE2018 – the 14th European Seminar on Personal Protective Equipment (PPE). Saariselkä, Finland, 23-25th January 2018.

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- Rissanen S, Jussila K, Kaisto J, and Rintamäki H. Individual finger cooling during cold exposure at rest. Manuscript being prepared.

Popular scientific publications:

- Intelligent clothing for extreme weather. Gemini (online magazine). 20th August 2015. http://geminiresearchnews.com/2015/08/utvikler-intelligente-ekstremklaer/
- Intelligent clothing for extreme weather. Science Nordic (online magazine). 4th September 2015. http://sciencenordic.com/intelligent-clothing-extreme-weather
- Intelligent clothing to protect Arctic workers. Maritime Direct (online magazine) 20th August 2015. https://www.maritime-executive.com/article/intelligent-clothing-to-protect-arctic-workers#gs.bquk8sg
- Article in Norwegian on the Norwegian Broadcasting (NRK) 1th August 2015. https://www.nrk.no/trondelag/utvikler-smarte-klaer-til-ekstremvaer-1.12480760
- Article in Norwegian in Byggfakta (Building and Construction magazine) 27th July 2015. https://www.byggfakta.no/intelligente-ekstremklaer-88829/nyhet.html
- Newsletter published at FIOH web news in Finnish 24th November 2015: http://www.ttl.fi/fi/uutiset/Sivut/alykkaita_suojainratkaisuja_kylmatyohon.aspx
- Article in Finnish in Kansanuutiset (9.12.2015): http://www.kansanuutiset.fi/artikkeli/3474220-minkalainen-kasine-alyaa-kylmaa

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ANNEX 1

Work Package 1 – Indication of critical level of cold

Towards a wearable sensor system for continuous occupational cold stress assessment

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This study investigated the usefulness of continuous sensor data for improving occupational cold stress assessment. Eleven volunteer male subjects completed a 90–120-min protocol in cold environments, consisting of rest, moderate and hard work. Biomedical data were measured using a smart jacket with integrated temperature, humidity and activity sensors, in addition to a custom-made sensor belt worn around the chest. Other relevant sensor data were measured using commercially available sensors. The study aimed to improve decision support for workers in cold climates, by taking advantage of the information provided by data from the rapidly growing market of wearable sensors. Important findings were that the subjective thermal sensation did not correspond to the measured absolute skin temperature and that large differences were observed in both metabolic energy production and skin temperatures under identical exposure conditions. Temperature, humidity, activity and heart rate were found to be relevant parameters for cold stress assessment, and the locations of the sensors in the prototype jacket were adequate. The study reveals the need for cold stress assessment and indicates that a generalised approached is not sufficient to assess the stress on an individual level.

Full original article:

Austad H, Wiggen Ø, Færevik H and Seeberg TM. Towards a wearable sensor system for continuous occupational cold stress assessment. Industrial Health 56 (3), 2018, p. 228-240.

https://www.jstage.jst.go.jp/article/indhealth/56/3/56_2017-0162/_pdf/-char/en

Year-round activity involves challenging climatic conditions for the industries in the North. Especially in the winter cold disturbs not only the machinery of industrial processes and vehicles, but is also very crucial factor to reduce worker's thermal comfort, performance, and occupational health and safety. In the cold, work capability and productivity decrease, the risk of mistakes and errors increases and stress level elevates. Peripheral body parts, such as hands, are the first to cool when humans are exposed to cold resulting in reduced manual and psychomotor performance.

This report describes possibilities of sensor-based heating systems integrated into gloves to prolong the safe and efficient working time in the cold.

The project was carried out in co-operation with SINTEF and it was part of Saf€ra program.

Työsuojelurahasto
Arbetarskyddsfonden
The Finnish Work Environment Fund

Työterveyslaitos
Arbetshälsoinstitutet
Finnish Institute of Occupational Health

PL 40, 00032 Työterveyslaitos

www.ttl.fi

ISBN 978-952-261-818-4 (nid.)
ISBN 978-952-261-817-7 (PDF)