Clothing Physiological Properties of Cold Protective Clothing and Their Effects on Human Experience

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Kirsi Jussila

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Thesis for the degree of Doctor of Science in Technology to be presented with due permission for public examination and criticism in Festia Building, Auditorium Pieni Sali 1, at Tampere University of Technology, on the 26th of February 2016, at 12 noon.

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Abstract

Approximately one third of the Finnish working population is exposed to cold ambient temperatures (<+10 °C) at their work due to natural or artificial environments. The longest cold exposure times are experienced in construction and maintenance work, agriculture and forest industry, process industry, traffic and military personnel. Climatic changes in the Arctic are expected to take place in the future and thus the activity of several industries will be increased in the region. Without sufficient protection against cold, windy and moist ambient conditions, cooling of the workers causes discomfort and moreover will impair physical and mental performance. Cold protective clothing creates a microclimate around the worker, and it is required to prevent detrimental cooling and to enable the worker to maintain the thermal balance.

This thesis aimed to contribute new scientific information based on effects of clothing size, moderate wind and moisture on heat loss mechanisms through the layered cold protective clothing and how these affect the user's experience on thermal comfort, coping and performance. Finally, the thesis aimed to gather the obtained information and the most significant findings from holistic points of view to determine recommendations for future design and development of cold protective clothing.

The effects of layered cold protective clothing were examined from a multi-disciplinary perspective using textile technological and clothing physiological methods combined with thermophysiological and usability evaluation methods both in laboratory and in authentic field conditions. The measured materials consisted of layered fabric and clothing combinations, as well as different types of casualty coverings and protective gloves. The measurements were performed in the air temperature between −20 °C and +27 °C. Convective heat loss was studied in wind speeds of calm (0.3 m/s), moderate (4.0 m/s) and high (8.0 m/s). Effects of moisture from internal and external sources on clothing thermal insulation and heat loss were studied.

The study found that the inner layer influenced the most on moisture handling properties, such as heat content for evaporation, drying time, and decrease in thermal insulation when wet. Garment fit and size was shown to affect the thermal insulation by about 20% and it should be considered in standardisation for clothing size and testing of the cold protective clothing. Moisture transfer mechanisms and their effects on the clothing insulation in the cold differed whether the moisture appeared from internal or external sources of the clothing. Wind decreased the intrinsic insulation by up to 33% depending on material air permeability, body position and wind speed and direction. The study also showed that development of the cold protective clothing during several decades provided improved human experiences such as thermal comfort, coping and performance during long-term cold exposure. Well-being at work is supported also by comfort, which is emphasized by thermal and sensorial sensations in the cold climate. Therefore, the findings are significant for improving occupational safety, health, and well-being as well as productivity in outdoor processes.

Keywords

Requirements of Cold Protective Clothing, Layered Clothing, Thermal Insulation, Wind, Moisture, Size Optimizing, Design

Preface

This study was performed in several projects of Finnish Institute of Occupational Health (FIOH) in Oulu during 2008–2014. The author acknowledges the national and international funding for the projects in which the data were collected: Soldier in Cold: Health, Capacity and Protection (funding: Finnish Defence Forces); Maritime Casualty Covering and Evacuation (funding: Scientific Advisory Board for Defence); The Cooperation for Safety in Sparsely Populated Areas (funding: EU, Northern Periphery Programme); The Protection and Safety of Tourists and Tourism Workers (funding: EU, European Social Fund). I acknowledge the financial support provided for the dissertation-writing periods by The Finnish Work Environment Fund and Industrial Research Fund at Tampere University of Technology.

I would like to express my gratitude for my supervisor Docent Hannu Anttonen, Ph.D., for his passionate guidance, support, patience and time, especially during the final stages while writing the thesis. I am thankful to my supervisor Research Professor Ali Harlin, Ph.D., from Technical Research Centre of Finland and Tampere University of Technology, for his valuable advice and encouragement during this long process. I wish to acknowledge the pre-examiners of this thesis, Assoc. Prof. and Docent, Kalev Kuklane, Ph.D., Lund University, Sweden, and Assoc. Prof. and Co-Director Emiel den Hartog, Ph.D., Textile Protection and Comfort Center, College of Textiles, North Carolina State University, US, for their valuable comments and remarks.

I am grateful to all co-authors of the original papers from FIOH, Finnish Defence Forces and Centria University of Applied Sciences. I give special thanks to Docent Sirkka Rissanen, Ph.D., Helena Mäkinen, Ph.D., Erja Sormunen, Ph.D., and Anita Valkama, M.Sc., for the valuable discussions, help, support and critical commenting on original papers. I want to thank Pertti Tuhkanen for technical support of the measurement and Jouko Remes, M.Sc., for statistical expertise. I wish to thank Professor Hannu Rintamäki, Ph.D., and Docent Juha Oksa, Ph.D., for their guidance, support and encouragement. I also want to thank personnel in FIOH Oulu and Technological Safety and Protection Team providing relaxed and supporting working atmosphere. I want to express my respect for Docent Anneli Pekkarinen, Ph.D. (deceased), who was my mentor in FIOH at early stage of my studies. She provided support and encouragement at an early stage of the process, when it was difficult to find time and ways to study alongside the everyday work.

Finally, I want to express my warmest thanks to my family, my parents Lea and Kalevi, and my brothers, Mikko and Raimo, including their families, as well as my friends for the support and understanding throughout the process. Special thanks to folk dance group Polokkarit for providing always something else to think about.

Oulu, 22.12.2015

Kirsi Jussila

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List of Symbols and Abbreviations

Symbols

A	Surface area, m^2
C	Heat transfer by convection, W or W/m^2
C_{res}	Respiratory convective heat transfer, W/m^2
E	Heat transfer by evaporation, W or W/m^2
E_{app}	Apparent evaporative heat loss, W/m^2
E_{mass}	Evaporative cooling potential, W/m^2
E_{res}	Respiratory evaporative heat transfer, W/m^2
I_a	Thermal insulation of the boundary air layer, m^2K/W
I_{ar}	Resultant thermal insulation of the boundary air layer, m^2K/W
I_{cle}	Effective or intrinsic thermal insulation, m^2K/W
I_{cler}	Resultant effective thermal insulation, m^2K/W
I_t	Total thermal insulation from skin to ambient, m^2K/W
I_{tr}	Resultant total thermal insulation from skin to ambient, m^2K/W
H	Heat loss, W or W/m^2
H_t	Total heat loss, m^2K/W
$H_{t,dry}$	Total heat loss with dry clothing, W/m^2
$H_{t,wet}$	Total heat loss with wet inner clothing, W/m^2
K	Heat transfer by conduction, W or W/m^2
M	Metabolic rate, W or W/m^2
p	Clothing air permeability, mm/s
R	Heat transfer by radiation, W or W/m^2
R_c	Thermal resistance, m^2K/W
R_{et}	Water vapour resistance, m^2Pa/W

S	Heat storage, W or W/m^2
T_a	Ambient temperature, K or °C
T_c	Core temperature, K or °C
T_{cl}	Clothing surface temperature, K or °C
T_{sk}	Mean skin temperature, K or °C
$T_{Surface}$	Clothing surface temperature, K or °C
v	Wind speed, m/s
W	Mechanical work, W or W/m^2
w	Walking speed, m/s

Abbreviations

AG	Thickness of the air layer or air gap
ANOVA	Analysis of variance
CC	Control clothing
CV	Viscose
DLE	Duration limited exposure
FIOH	Finnish Institute of Occupational Health
IMP	Material combination consisting impermeable layer
IREQ	Required clothing insulation
LWC	Layered winter clothing
MPM	Micro porous membrane
PA	Polyamide
PBI	Poly benz imidazole
PCM	Phase change material
PERM	Permeable material combination
PES	Polyester
PMA	Phase memory alloys

PP	Polypropylene
PPC	Personal protective clothing
Rh	Relative humidity
RQ	Research question
SD	Standard deviation
SEMI	Material combination consisting of a semipermeable membrane
SMA	Shape memory alloys
SPSS	Statistical package for the social sciences
VAS	Visual analogue scale
WO	Wool

List of Original Publications

This thesis is based on the following five (5) original publications, presented as Papers I to V:

I. **Jussila, K.,** Anttonen, H. & Ketola, R. 2009. Functional underwear for military use in cold climate. Proceedings of NATO HFM-168 Symposium on "Soldier in cold environment", The National Defence University, Finland, Helsinki, 20–22 April.

II. **Jussila, K.,** Kekäläinen, M., Simonen, L. & Mäkinen, H. 2015. Determining the optimum size combination of three-layered cold protective clothing in varying wind conditions and walking speeds: Thermal manikin and 3D body scanner study. Journal of Fashion Technology and Textile Engineering, 3(2), pp. 1–9.

III. **Jussila, K.,** Valkama, A., Remes, J., Anttonen, H. & Peitso, A. 2010. The effect of cold protective clothing on comfort and perception of performance. International Journal of Occupational Safety and Ergonomics, 16(2), pp. 185–197.

IV. **Jussila, K.**, Rissanen, S., Parkkola, K. & Anttonen, H. 2014. Evaluating cold protective properties of different covering methods for prehospital maritime transportation – A thermal manikin and test subject study. Prehospital and Disaster Medicine, 29(6), pp. 580–588.

V. **Jussila, K.,** Sormunen, E. & Remes, J. 2013. Case study: perceived usability of emergency communication equipment with and without protective gloves in the cold. Journal of Search and Rescue, 1(2), pp. 1–15.

In addition, some unpublished data are presented in the thesis. Original papers were reprinted with the permission of the publishers.

Author’s Contributions

Paper I, *“Functional underwear for military use in cold climate”* presents the material properties of different underwear fabrics for cold conditions. The author planned tests of textile materials, analysed results and wrote the manuscript, which was commented on by the co-authors.

Paper II, *“Determining the optimum size combination of three-layered cold protective clothing in varying wind conditions and walking speeds − Thermal manikin and 3D body scanner study”* examines the influence of clothing size of the layered clothing system on thermal insulation properties. The author planned the measurement setup, participated in the execution of the measurement, analysed the results in part of thermal insulation in different measurements conditions and wrote the manuscript, which was commented on by the co-authors.

Paper III, *“The effect of cold protective clothing on comfort and perception of performance”* describes significance of clothing type, design and different materials on the user’s thermal and moisture sensations and perceived physical and mental performance. The author analysed the questionnaire results and wrote the manuscript, which was commented on by the co-authors.

Paper IV, *“Evaluating cold protective properties of different covering methods for prehospital maritime transportation – A thermal manikin and test subject study”* evaluates clothing physiological properties of ten different casualty coverings, the need of thermal protection for a casualty and to verify the optimum covering system for prehospital maritime transportation. The author was responsible for planning the measurement setup in the laboratory and cooperated in the execution of the measurement both in laboratory and field measurements, analysed the results in part of thermal insulation in different measured conditions and was corresponding author of the paper, which was co-written and commented on by the co-authors.

Paper V, “*Case study: Perceived usability of emergency communication equipment with and without protective gloves in the cold”* studies the effects of different types of gloves and their material cooling on manual performance and dexterity. The author planned the measurement setup and produced the tests in co-operation with the co-authors and other professionals from different fields of expertise. The author planned and executed the dexterity tests of the different gloves in warm and cold temperatures. The author analysed results in part of the textile materials of gloves, and the effects on finger dexterity. The author was corresponding author of the paper, which was co-written and commented on by the co-authors.

1 Introduction

1.1 Background and Hypothesis

Over 30% of the Finnish working population is exposed to the cold (<+10 °C) during their working time, in both outdoor and cold indoor work. The longest cold exposure times (>15 h/week) are experienced in construction and maintenance work, agriculture and forest industry, process industry, traffic and military workers (Hassi et al., 1998). Cooling causes discomfort and moreover will impair physical and mental performance in different ways. Further, severe cold exposure can lead to cold-related symptoms and injuries, such as frostbite, hypothermia and cold-related accidents. Detrimental cooling and cold-related injuries are preventable by appropriate cold risk management, which takes into account adverse effects of cold, individual adjustment of cold exposure, clothing and other organizational and technical measures (Ikäheimo and Hassi, 2011).

Selecting the correct clothing requires an understanding of the properties of different clothing materials and how they form a layered cold protective clothing system. Cold protective clothing creates a microclimate around the worker. This microclimate must prevent detrimental cooling and enable the worker to maintain the thermal balance. Insufficient thermal insulation will allow the body to cool, whereas thermal insulation that is too high will result in sweating during physically demanding tasks. The size of the clothing and thickness of the air layer entrapped between the layers will affect both thermal insulation and the water vapour permeability of the clothing ensemble. The more trapped still air is in the clothing and the fabrics, the higher is the thermal insulation. Even though cold protective clothing is needed to prevent cooling of the body, it is important to recognize the detrimental effects of clothing on physical performance, energy consumption, manual dexterity and sensory function, and limitations on movement, visual field and comfort due to weight and stiffness of the clothing material and friction between the layers (Dorman and Havenith, 2009; Duggan, 1988; Havenith et al., 1995; Rissanen, 1998).

Cold environments can be classified as natural, such as outdoor activities, or artificial, such as cold stores. Natural cold varies from mild and moist to dry and extremely cold, and thermal protective clothing has to vary accordingly. Environmental factors, such as wind, convey heat away from the clothing and compress the air layers underneath outer garments, whereas water and dirt block fabric construction, increase thermal conductivity and evaporate heat away from clothing. Figure 1 presents both environmental and human physiological factors influencing clothing properties and microclimatic conditions which create a feeling of comfort and support the performance, health and safety of the user.

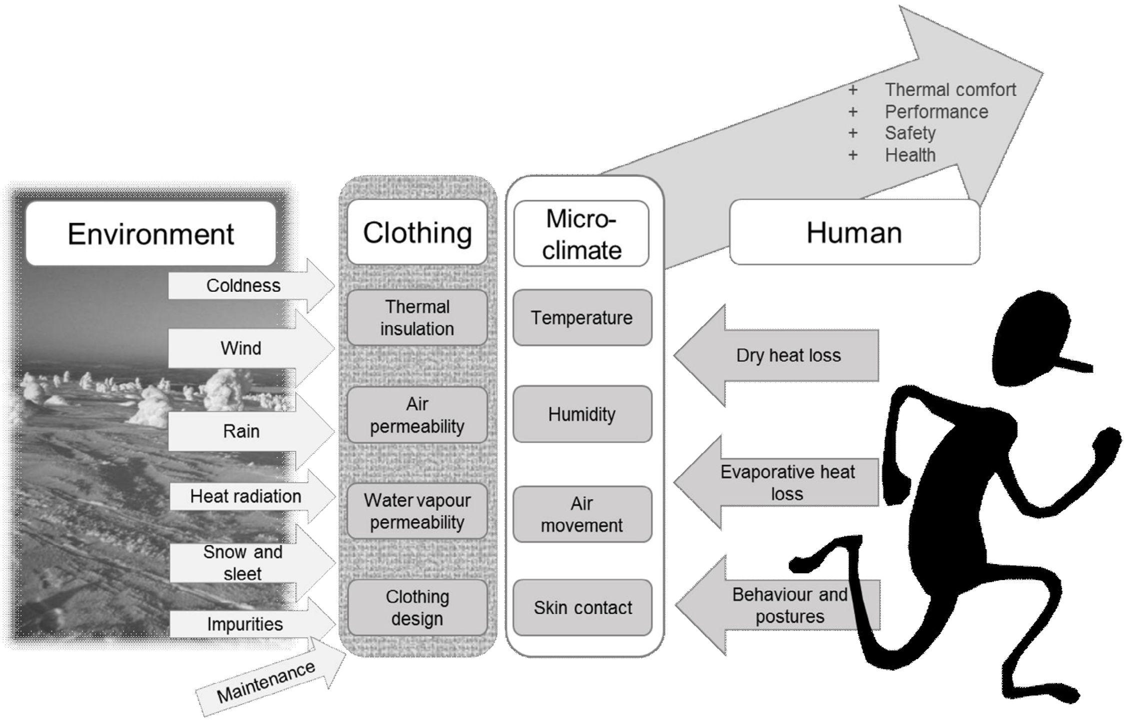

Figure 1. Effects of environmental and human physiological factors on textile properties and microclimatic conditions.

Climate is changing with time and strong wind speeds, storms and heavy rains have become more common also in the Northern areas. These climatic changes also modify demands for the protective properties of cold protective clothing. Sufficient protection of workers against cold, high wind speeds and rain in these exceptional conditions is essential to maintain comfort and physical effectiveness at work, and thereby providing economic benefits for the industry, for example in the electric power supply, mining and maritime industries. Changes in the Arctic are expected to take place in the future and these will expand the activity of several industries in the region. This will increase the amount of workers in the cold climate and some of them will come from areas where the people are not used to these conditions.

In this thesis, is examined the effects of layered cold protective clothing from a multi-disciplinary perspective using textile technological and clothing physiological methods combined with thermophysiological and usability evaluation methods. It was hypothesized that clothing physiological properties of textiles and clothing combinations, and their correct selection, can improve a worker's thermal comfort, coping and performance in the cold. It was essential to identify the effects of the work environment (cold, wind and moisture) and the worker him or herself on heat transfer (radiation, convection, evaporation) through the cold protective clothing. The protection of outdoor workers, such as soldiers, rescuers and winter tourism workers, is focused on in this thesis.

1.2 Objectives and Research Questions

This thesis contributes new scientific information and points of view on clothing physiology and protective clothing in cold work:

- evaluating the obtained results and detailed clothing physiological parameters from a holistic point of view as part of comfort and well-being at work,
- using multi-disciplinary fields of research combining textile technological, clothing physiological, thermophysiological and usability evaluation methodologies,
- applying research methodology from fabric evaluation in the laboratory to clothing evaluation on a thermal manikin and on humans in authentic ambient conditions,
- producing applicable recommendations into the practice based on scientific testing and evaluation methods and, moreover, improving well-being in Arctic work.

The main objective of this thesis was to identify effects of clothing size, moderate wind and moisture on heat loss mechanisms through the layered cold protective clothing. Secondly, it was aimed to find how these affect the user's thermal comfort, coping and performance and to clarify which clothing physiological properties were critical in supporting these users' experiences in cold work. The final aim was to determine recommendations for future design and development of cold protective clothing on the basis of the most significant findings of this thesis.

The research questions addressed in this thesis were formed and they were answered with Papers I–V as presented in Table 1. Each original paper provides a partial solution to the research problem. The contributions of these articles are combined in this dissertation summary.

Table 1. Research questions of this thesis.

	Research question	**Paper**
RQ1	What are the most important clothing physiological functions of the inner layer as part of layered clothing to take into account in subzero temperatures?	I
RQ2	How does the size of the different clothing layers affect dry heat transfer in static and dynamic situations?	II
RQ3	How does moisture from internal and external sources affect heat transfer through clothing in subzero temperatures?	IV
RQ4	How does wind and its direction affect dry heat transfer through layered clothing?	II, IV
RQ5	Are the found effects on properties of layered clothing significant for the user's thermal comfort, coping and performance?	III, IV, V

1.3 Structure of the Thesis

This thesis is based on five scientific publications in refereed journals and one refereed proceeding. It contains a summary, which pulls together a literature review, and an experimental and resulting sections. The structure of the thesis is formed from the basis of a wide scope of theoretical background to detailed findings due to empirical studies. The thesis is structured as presented in Figure 2.

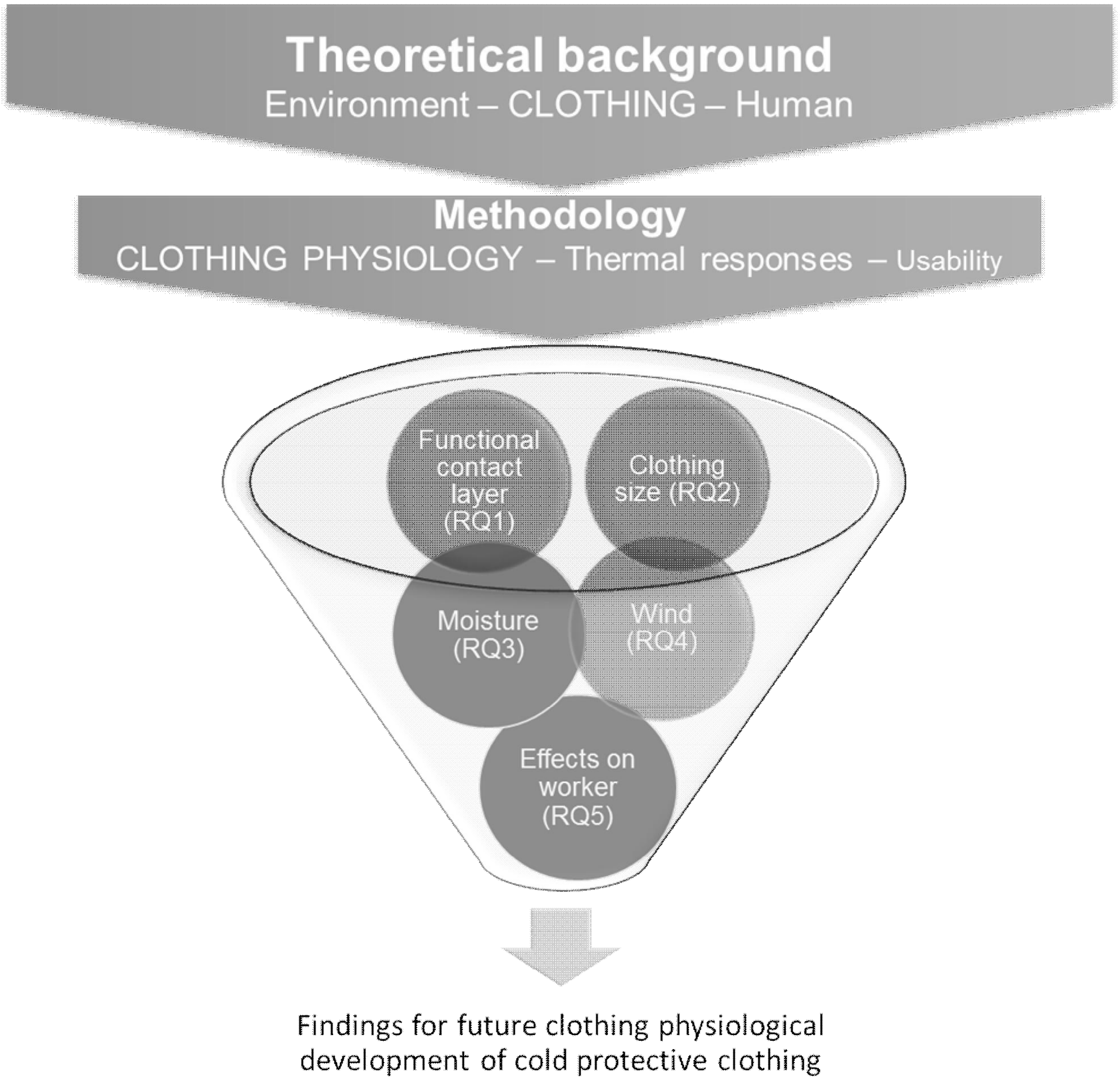

Figure 2. Structure of thesis from wide scope to detailed findings.

2 Review of the Literature

Influences of cold work environment on workers' health and safety and cold risk management by cold protective clothing are described in this chapter. Particularly, this chapter concentrates on summarizing specific information from literature on clothing physiological properties of layered cold weather clothing and factors affecting them. In addition, effects of different type of clothing on user's thermal comfort, coping and performance will be identified on the basis of the literature. At the end of this chapter will be described recent trends and development of cold protective clothing.

2.1 Work in the Cold

2.1.1 Cold Exposure at Work

Work is considered as cold work at temperatures lower than +10 °C, according to a standard (BS 7915, 1998). The Finnish population is exposed to cool and cold temperatures during the winter season from 180 to 270 days (Mäkinen et al., 2006b). More than 30% of the Finnish working population are exposed to the cold during their occupation, both outdoor and cold indoor work. The longest cold exposure times are experienced in construction and maintenance work (>20 h/week). Also cold exposure of more than 15 h/week is common in agriculture and forest industry, process industry, traffic and military personnel (Hassi et al., 1998).

To be exposed to the cold is common when working outdoors in the northern areas several months per year. In these conditions also wind, wettedness, cold materials and contact surfaces are common (Anttonen et al., 2009). Cold exposure indoors is common in the food industry, where fresh food is processed in temperatures from zero to +10 °C and frozen products at below −20 °C

(Oksa et al., 2006; Piedrahita et al., 2008). It is very typical in several professions that environmental conditions and the physical activity level varies radically within a work shift (EN ISO 11079, 2007).

2.1.2 Cold-Related Occupational Hazards and Benefits

A cold environment causes several effects on humans. Cooling will first cause unpleasant sensations and discomfort (Lotens, 1988), and, moreover, when prolonged it will lead to impaired physical performance (Oksa, 2002), work ability (Sormunen et al., 2009) and cognition (Mäkinen et al., 2006a). Further, severe cold exposure can lead to cold-related symptoms and injuries, such as frostbite, hypothermia and cold-related accidents (Anttonen et al., 2009; Hassi et al., 2000).

The most common cold-related complaints among Finnish population were musculoskeletal pain and symptoms of respiratory conditions, white fingers and episodic peripheral circulatory conditions (Raatikka et al., 2007). In Finland, cases of frostbite were reported the most in occupations such as agricultural and fishery workers, craft and related trades workers, plant and machinery operators, assemblers and technicians (Mäkinen et al., 2009). The literature reveals that a high risk of frostbite have been commonly reported among reindeer herders (annual incidence 22%) (Ervasti et al., 1991) and in military training and operations (Candler and Ivey, 1997; Lehmuskallio et al, 1995; Schissel et al., 1998; DeGroot et al., 2003). Based on a self-reported questionnaire the overall annual proportion of mild frostbite was about 13% and severe frostbite about 1% (Mäkinen et al., 2009). Approximately 30% of frostbites reported in military operations were on fingers (Juopperi, 2006). It was also shown that frostbite occurs more often in men than women, among smokers and those having been exposed to vibration, and it is related to age as well (Juopperi, 2006). Hypothermia is not common among workers, but can occur in cases of prolonged cold exposure, wind and wetness (Brändström and Björnstig, 1997).

The cold-related risks can be reduced by cold risk management, which takes into account adverse effects of cold, individual adjustment of cold exposure and clothing, and other organizational and technical measures (Anttonen et al., 2009; Ikäheimo and Hassi, 2011). Prevention of cold-related health risks and body cooling as well as sustaining work performance can be implemented by appropriate cold protective clothing and devices (Anttonen et al., 2009). At the same time it is important to recognize disadvantages of clothing on performance, manual dexterity, sensory function, limitations on movement, energy consumption, and comfort, which is described in more detail later in Chapter 2.4 (Dorman and Havenith, 2009; Duggan, 1988; Havenith et al., 1995; Rissanen, 1998).

2.2 Cold Protective Clothing

2.2.1 Functional Clothing System

The purpose of cold protective clothing is to prevent the effects of cold combined with wind and moisture. The base of the clothing is fibre material formed into yarns, which are finally produced into porous knitted or woven fabric constructions. The thermal resistance is shown to be higher when more air is trapped in the fibres, fabric structures and clothing system (Farnworth, 1983). Functional cold protective clothing consists of at least three separate layers: inner, mid and outer layers. The layered clothing enables the level of clothing insulation to be adjusted depending on the physical activities and ambient conditions. Thus, the materials for each layer have to be carefully selected (Bougourd and McCann, 2009; Holmér, 2011; Jussila and Rissanen, 2012; Wu and Fan, 2008).

Inner layer

The inner layer is the functional part of the cold protective clothing and it is affected by mid and outer garment layers (Laing et al., 2011). The inner layer is exposed to heat, water vapour and liquid exchange from the skin. The main function of the inner layer is to keep the user's skin dry and improve thermal and moisture sensations on the skin and, therefore, it may significantly affect comfort sensations (Stanton et al., 2014). High heat and sweat production during physical activity lead to sweat accumulation in the garments and its distribution is dependent on the fibre composition, yarn and fabric construction, clothing design of the inner garment as well as environmental conditions (Bakkevig and Nielsen, 1994 and 1995; Frackiewicz-Kaczmarek et al., 2015; Ha et al., 1998; Lotens and Havenith, 1995; Stapleton et al., 2011). Accumulated moisture increase wet cling of the inner fabric causing mechanical irritation with the skin (Lou et al., 2015). Increased skin moisture content and skin temperature have shown to cause prickle sensation (Westerman et al., 1984). As well as the sensation of prickle is identified to be in relation to fibre diameter (Naylor et al., 1997) and is identified to be evoked by fabric as a mechanical interaction between fibre ends protruding from the fabric surface and the skin (Garnsworthy et al., 1988; Stanton et al., 2014).

Suitable inner layer material for cold climate should provide good tactile properties, high wicking properties, lightweight and non-compressible (Goldman, 2007; Keiser et al., 2006; Nielsen and Madsen, 1992). It has been studied that cotton (CO) with naturally absorbent fibre construction as an inner layer under winter clothing led to lower skin temperatures during recovery after walking and higher moisture content than a hydrophobic polypropylene (PP) inner layer, whereas PP resulted in higher metabolic production than with CO (Ha et al., 1996 and 1998). Highly hygroscopic woollen fabrics have proven dryer perception and skin temperature when wet than weakly hygroscopic polyester (PES) (Li et al., 1992). Wool is naturally flexible and breathable due to its fibre construction (Laing, 2009). Itching of the woollen fabric is prevented by using merino fibres thinner than 23 µm, because the fibre ends bend when touching the skin (Bergh, 2007).

Mid layer

The mid layer can consist of different insulating layers creating the level of thermal insulation of the clothing. The mid layers are permeable materials with porous fabric constructions trapping still air in the clothing system (Bougourd and McCann, 2009). Wool is often used material in mid layer due to its fibre structure and crimp that can contain still air inside the fibre. Whereas fleece materials made of polyester have good thermal insulation properties due to its porous fabric construction.

To improve moisture handling properties of the clothing it is suggested that by using wool instead of polyester or down as an inner batting material, dryer micro climate while sweating is created due to the strongly hydrophilic nature of wool (Wu and Fan, 2008; Kofler et al., 2015). In addition, Kofler et al. (2015) were able to show that use of wool in the batting led to an attenuated core and skin temperature drop after physical exercise, and thus the after chill effect was reduced.

Outer layer

The outer layer protects against cold, wind and moisture and it has the most complex structure. The outer layer is often required for protection against wind and moisture from external sources as well as permeability of moisture vapour due to sweating (Bougourd and McCann, 2009). In the literature has been discussed the use and benefit of the semi-permeable membranes in the cold climate, especially while and after sweating. Bartels and Umbach (2002) proposed that permeable fabric constructions provide a clear benefit to wearers and breathable membranes have sufficient moisture transport at low temperatures as well (−20 °C). They showed that moisture accumulations were much lower with material combinations consisting of a breathable membrane than with non-breathable systems. If a membrane was attached in four and five layer fabric combinations, moisture accumulated mostly in the third and secondly in the fourth layers from the skin (Rossi et al., 2004; Yoo and Kim, 2008 and 2012). If an outer membrane was attached to the insulating layer of the multilayer clothing system, vapour permeability increased and moisture accumulations decreased in cold climate after sweating period. It was also reported that moisture accumulation profiles in a multilayer clothing system were affected by layer arrays, such as air layers between the layers. They found that the moisture accumulations were least when the fifth membrane-layer was attached to the fourth fleece-layer (Yoo and Kim, 2008 and 2012).

2.2.2 Requirements for Clothing against Cold

The requirements of cold protective clothing are determined based on the ambient conditions (air temperature, wind, moisture, cold surfaces), cold exposure times, physical activity, and ergonomics during the activity as well as demands of the legislation and standards to maintain users' thermal balance, comfort and work ability in the cold (Mäkinen and Jussila, 2014). Working postures and ergonomics have an effect on thermal insulation by compressing air layers inside the clothing. In addition, individual differences in body anthropometrics present challenges in clothing design and patterning especially in protective clothing (Bourgourd and McCann, 2009).

Required thermal insulation in different air temperatures, wind speeds and physical activity to maintain the thermal balance can be calculated based on equilibrium as described in standard EN ISO 11079 (2007):

$$IREQ = \frac{T_{sk} - T_{cl}}{M - W - E_{res} - C_{res} - E} = \frac{T_{sk} - T_{cl}}{R + C} \qquad (1)$$

where T_{sk} is mean skin temperature (°C), T_{cl} is clothing surface temperature (°C), M is metabolic rate (W/m^2), W is mechanical work (W/m^2), E_{res} is respiratory evaporative heat transfer (W/m^2), C_{res} is respiratory convective heat transfer (W/m^2), E is evaporative heat transfer due to sweating (W/m^2), R is radiation heat transfer (W/m^2) and C is convective heat transfer (W/m^2).

Index for 'required clothing insulation' (IREQ) set two different values: $IREQ_{neutr}$ and $IREQ_{min}$. The $IREQ_{neutr}$ determines the required thermal insulation to maintain thermal balance during long-term cold exposure (8 hours) in given conditions, whereas the $IREQ_{min}$ provides value for minimum thermal insulation to maintain body heat balance at a subnormal level of mean body temperature and allows the thermal sensation to be 'slightly cool'. In this case, cooling of the extremities may become the limiting factor during prolonged exposure. In addition, index for 'duration limited exposure' (DLE) can be determined to express the time of cold exposure when using the certain level of thermal insulation (EN ISO 11079, 2007).

Working in the cold sets specific organisational, technical and personal requirements to prevent cooling and cold-related hazards. The employers' obligatory responsibilities in general terms are defined in the council directive 89/391 (EEC, 1989a) to ensure workers' health and safety at work, whereas the directive on personal protective equipment (PPE) (Commission Directive 89/686/EEC, 1989b) determines the basic safety demands for all PPE as well as specific material and component requirements as well as for complete PPE intended for use in the cold. Four standards consisting of requirements for protective clothing and gloves against cold and harsh weather conditions have been produced to support the requirements of EU Directive 89/686/EEC: EN 342 (2004) Ensembles and garments for protection against cold, EN 14058 (2004) Garments for protection against cool environments, EN 343 (2003) Protective clothing – Protection against rain, and EN 511 (2006) Protective gloves against cold.

2.3 Clothing Physiology

Clothing physiology is an interdisciplinary evaluation method to maintain and improve a user's thermal comfort and thermal balance. Clothing physiological analysis takes into account interaction of humans, environment and clothing. It is used for design, development and selection of textile materials and clothing. Clothing physiological research methods are fabric tests and thermal model measurements in laboratory and climatic chamber, test subject measurements in laboratory and field conditions, and mathematical models and indices. Final properties of the clothing are affected by model, design and details of the garments (Holmér, 1989).

2.3.1 Heat and Moisture Transfer in Fabrics

In the cold, climate personal protective clothing (PPC) is worn to prevent body heat transfer from human body to environment. However, thermal and moisture transfer occurs due to dry heat loss by convection, conduction and radiation, and due to moisture transportation (Chen et al., 2003; Fukazawa et al., 2004; Havenith et al., 2008; Meinander and Hellsten, 2004; Richards et al., 2008). Heat and moisture transfer occurs through pores of textile, fibre interior and surface, capillaries between fibres and yarns, and air between fabrics and yarns (Rossi, 2009). The fabric properties can significantly affect humidity and temperature distributions, as well as comfort (Wang et al., 2007). In several studies (Havenith et al., 2008; Havenith et al., 2013; Richards et al., 2008) the mechanisms of heat and moisture transfer from the skin to environment have been modelled, as presented in Figure 3.

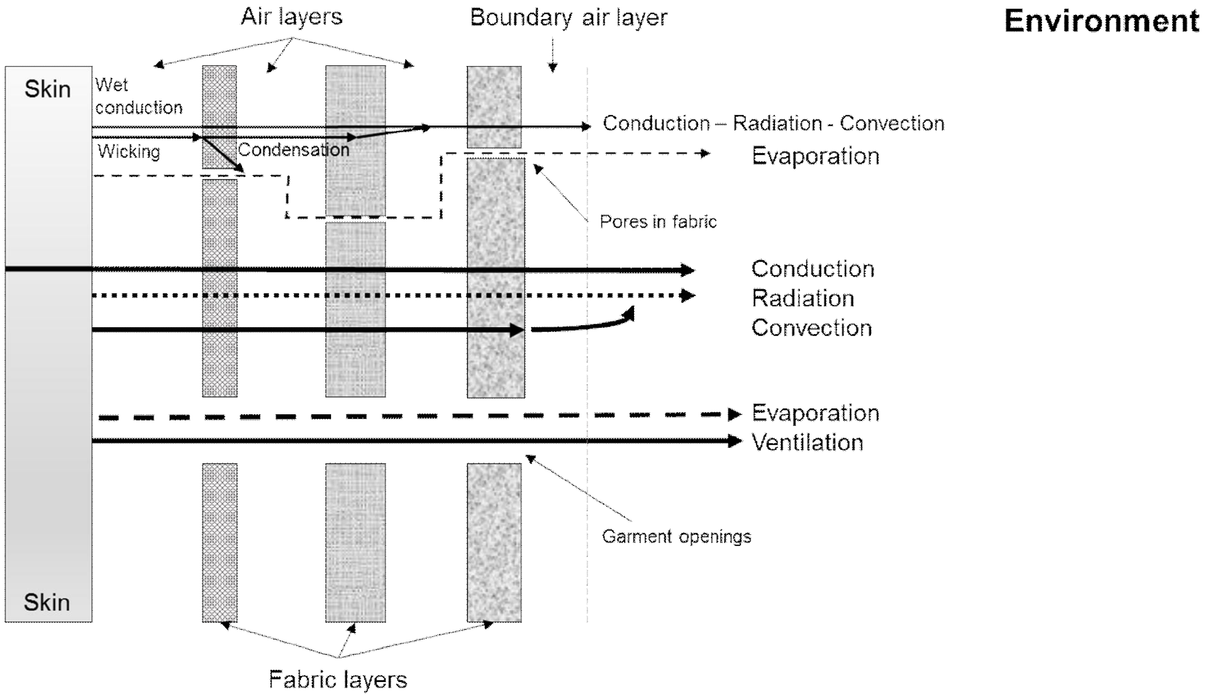

Figure 3. Heat and moisture transfer mechanisms from skin to environment.

Dry heat transfer occurs due to a complex physical process from the skin through textile materials to the ambient air. Heat transfer in fabrics refers to the rate of energy that is moved from a high temperature medium to a low temperature medium. It contains heat convection between textile layers, direct and indirect heat radiation from fibre to fibre in air layers between textile materials and heat conduction through textile fibres (Song, 2009). The microclimate between the skin and clothing layers has the highest importance on heat transfer efficiency, and textile fibre properties are only secondary.

The moisture transfer through clothing combines several complex mechanisms, such as diffusion, absorption, wicking and migration of water vapour molecules and liquid water, and evaporation, condensation, sorption and desorption of moisture (Chen et al., 2003; Fukazawa et al., 2004; Havenith et al., 2008; Meinander and Hellsten, 2004; Richards et al., 2008). Moisture diffuses through the air spaces in the yarns and fabrics. Textiles with open structure typically allow more rapid diffusion of moisture than closed structures (Song, 2009). Sweating increases the total heat loss by evaporative heat loss and wetting of the clothing and the effect is more significant at very low temperatures (−50 to −25 °C) than temperatures between −10 °C and 0 °C (Meinander and Hellsten, 2004). In addition to ambient temperature, relative humidity has a great effect on moisture transfer through a multilayer clothing system and increases exponentially moisture condensation in clothing at lower temperatures (+1…+20 °C) (Rossi et al., 2004). The condensed moisture increases conductivity of the clothing and forms a cycle of moisture evaporation and condensation (Richards et al., 2008).

2.3.2 Thermal Insulation

Clothing prevents heat transfer between human and environment, which is determined by thermal insulation of the clothing. Thermal insulation is nowadays expressed in SI-units by m^2K/W. It has been generalized that a warm business suit provides thermal insulation of approximately 0.155 m^2K/W for the whole body, which was originally equal to 1 clo unit (Gagge et al., 1941). The total thermal insulation (I_t) of the clothing and boundary air layer surrounding the clothing surface in stationary situations is defined by the equation:

$$I_t = \frac{(T_{sk} - T_a) \cdot A}{H} \tag{2}$$

where A is surface area (m^2), T_{sk} is mean skin temperature (K), T_a is ambient temperature (K), and H is heat loss (W).

A thin insulating boundary air layer is formed in contact with a solid material and it surrounds both an unclothed and clothed body. The thermal resistance (I_a) of the boundary air layer corresponds with the thin clothing layer. The thickness of the boundary air layer in calm wind conditions is about 4−8 mm. To determine the intrinsic or effective thermal insulation (I_{cle}) of the clothing from skin to outer clothing surface in stationary situations, the following equation is used (EN ISO 15831, 2004):

$$I_{cle} = I_t - I_a \tag{3}$$

Fibres forms on average about 5–20% of the efficient thermal insulation of the cold protective clothing system, whereas trapped dry and still air into fabrics and between garment layers forms on average about 80–95% (Cooper, 1979) due to about eight times higher thermal resistance of the air than fibre materials (Song, 2009). The air volume underneath the clothing increases by adding clothing layers, but also fibre physical properties, such as diameter, length, crimp, length and shape, as well as the yarn and the fabric structure. Garment fit and high air content in the clothing system increase the thermal insulation (Chen et al., 2004; Havenith et al., 1990b; Kuklane et al., 2004; Lee et al., 2007; Meinander et al., 2004), but the insulation starts to drop beyond an optimum air layer thickness (Chen et al., 2004; Lee et al., 2007). Clothing size, and thus, volume of the dry, still air in microclimate, is a significant factor when aiming for maximum thermal insulation of the cold protective clothing (Chen et al., 2004; Meinander et al., 2004).

Air layers inside the clothing are not evenly distributed over the body and there are more small air gaps than large ones (Mah and Song, 2010). Air content in the clothing can be measured by pinching the fabric from different points of the body or by calculating from the difference between the clothing measure and manikin or test subject (Chen et al., 2004). This method is accurate, fast and cheap to perform. However, it does not provide any information on the shape and position of the garment circumference. Recently, 3D body scanning methodology has been used to analyse garment fit and air gaps inside the clothing. The method has proven to give comparable results with manual measurements and to be a valuable tool for objective ratings and fit evaluation of garments (Ashdown et al., 2004; Ashdown and Dunne, 2006; Lee et al., 2007; Mah and Song, 2010; Nam et al., 2005; Psikuta et al., 2015; Robinette and Daanen, 2006).

A simple approach to evaluate the thermal insulation is based on material thickness. The thermal insulation of the materials is almost directly related to the fabric thickness under dry conditions (Havenith, 2002b). Based on analysis of thermal manikin measurement data, a practical method to estimate the thermal insulation by weighing the clothing without shoes, if the weight is less than four kilograms, has been developed (Olesen, 1980).

Physical thermal manikin measurements for single garments and clothing ensembles in controlled climatic conditions are used for development and comparison of different clothing combinations. The thermal manikins vary in size, shape and technology, and they are divided into 16–30 individual body segments (Havenith, 2009). Comparing the results from thermal manikin measurements with dry and moist clothing corresponds well with human wear trials at moderate temperatures between −10 to 0 °C, and the reproducibility of the tests has shown to be good (Anttonen, 1999; Anttonen et al., 2004; Meinander et al., 2004; Meinander and Hellsten, 2004).

Clothing physiological measurements in laboratory or authentic field environment with human wear trials are necessary when evaluating clothing effects on thermal responses and comfort of the users. Human trials may consist of subjective judgement of thermal factors (EN ISO 10551, 2001), physiological wear trials as well as heat balance measurements. The number of human test subjects for physiological tests should be at least 8–10 to find statistically significant differences between evaluated ensembles (Holmér, 2009). Clothing insulation of the clothing system on a human subject is calculated based on measured mean skin temperatures and mean heat flow from the skin during performed activities (Jussila and Rissanen, 2012; Rissanen and Jussila, 2012).

2.3.3 Moisture Handling Properties

Moisture into the clothing may occur internally due to sweating or externally due to snow, sleet, ice rain, or water splashes in maritime conditions in subzero ambient temperatures. In neutral and resting conditions, evaporative moisture from a human is half a litre per day (about 30 g/h). Most of the moisture evaporates from the skin. During a short period of high physical activity, the body can produce 4−5 litres of perspiration. For a long period of high physical activity, moisture perspiration is about one litre per hour (Ilmarinen et al., 2011). A great increase in evaporative cooling efficiency occurs when moisture is absorbed from the skin and the heat of evaporation is taken from the body (Chen et al., 2003; Havenith et al., 2009). This may lead to a critical cooling of the body.

Heat loss from wet clothing occurs simultaneously due to moisture evaporation and dry heat loss. When the temperature gradient between skin and ambient increases, the amount of dry heat loss rises and moisture evaporation reduces (Havenith et al., 2008; Richards et al., 2008). Moisture condensation into clothing depends on ambient temperature and saturation vapour pressure distribution within the clothing and the highest moisture accumulations occurs under the outer layer (Rossi et al., 2004; Yoo and Kim, 2008 and 2012). This increases conductivity of the materials and dry heat loss through clothing.

Moisture in textile material decreases thermal insulation in proportion to moisture retention by replacing air with water in the material, compressing garments and increasing material thermal conductivity (Chen et al., 2003; Thomassen et al., 2011). Water (0.58 W/mK) has 24 times higher thermal conductivity than air (0.024 W/mK) at the same temperature (+25 °C). Decrease in thermal insulation is also caused by enhanced heat conductivity (Bartels and Umbach, 2002). When moisture content reaches about 15%, thermal insulation is about 50% of the dry thermal insulation value (Ilmarinen and Tammela, 1997). This phenomenon does not differ significantly between fibre materials, but fibre materials have major differences in moisture absorption properties.

Water vapour resistance, R_{et}, describes material resistance to moist heat transfer through fabric. The R_{et} is varied depending on fabric thickness and construction density, and both chemical and physical properties of fibres. The R_{et} of conventional clothing fabrics is about between 4–9 m^2Pa/W, and corresponding value of fabrics with semi-permeable membranes is between about 9–20 m^2Pa/W (Ilmarinen et al., 2011). Water vapour transfers from the inner side to the fabric surface due to fabric construction or garment holes (diffusion), fibre absorption and fibre surface. Rossi et al. (2004) found that at low ambient temperatures, water vapour resistance of the multi layered ensembles increases greatly, and moisture accumulations in the clothing increase exponentially. Colder air can store less moisture until saturation is reached than warm air (Rossi, 2009).

A higher vapour pressure in a micro porous membrane (MPM) fabric is attributed to condensation, which blocks the pores that transport water vapour, than fabrics that have a higher thermal insulation and air permeability, such as fleece (Kim et al., 2006). An evaporative barrier in protective covering hinders moisture transfer to the outer layers, hence leading to moisture condensation and thus reduced insulation capacity (Thomassen et al., 2011). Accumulated moisture is reported (Bartels and Umbach, 2002) to freeze beneath foul weather protective garments during wear trials at −20 °C due to condensation of evaporative sweating. The dew point was reached within the clothing due to low ambient temperature and high temperature gradient.

2.3.4 Effects of Wind and Body Movement

Wind increases convective heat loss from clothing, compresses the clothing layers and thus decreases air content inside the clothing and moreover decreases the thermal insulation of the clothing (Anttonen, 1993; Anttonen and Hiltunen, 2003; Havenith et al., 1990b; Havenith and Nilsson, 2004; Henriksson et al., 2009). Due to convection the insulating boundary air layer surrounding the body became thinner and the total thermal insulation decreases (Ilmarinen et al., 2011). If wind penetrates through the fabrics or gets in through garment openings, such as sleeve ends, jacket hem or ventilation holes, thermal insulation will be impaired by convection and the ‘chimney effect’ under the clothing. The ‘chimney effect’ occurs when warm air in the micro climate transfers upward and is replaced with cold air from the atmosphere (Fanger, 1970).

The significance of air permeability of clothing materials is most pronounced at higher wind speeds and higher levels of physical activity, where heat loss needs to be increased. Air permeability of textile materials is formed by fabric construction, gauge, thickness, finishes, and different laminates, membranes and coating (Lomax, 2009). Open structured fabrics have high air penetration, whereas laminated or coated fabrics are impermeable. Garment design and pattern have an influence on the air permeability of the clothing. Tightly closable sleeves, legs, jacket hem- and neckline improve protection against wind. Anttonen and Hiltunen (2003) have shown that clothing thermal insulation decreases in a wind speed of 18 m/s by about 70% with air permeable 3-layered clothing and with clothing integrated with micro porous membrane (MPM) the corresponding decrease was 50%.

Body movement or walking causes a reduction in clothing thermal insulation due to movement of warm air layers and ventilation inside the clothing (Havenith et al., 1990b; Havenith and Nilsson, 2004; Reed et al., 2007), as well as due to reduced or removed boundary air layer (Hänel and Holmér, 1986). Thick clothing shows stronger reductions in insulation due to posture and movement than ensembles with low insulation values (Havenith et al., 1990b). In moving situations the resultant thermal insulation values are used to determine the total thermal insulation (I_{tr}), insulation of boundary air layer (I_{ar}) and the effective thermal insulation (I_{cler}). Nilsson et al. (2000) have originally presented an equation for resultant thermal insulation (I_{tr}) of the cold weather clothing (1.49 clo < I_t < 3.46 clo):

$$I_{tr} = [0.54 \cdot e^{(-0.12v-0.22w)} \cdot p^{0.075} - 0.06 \cdot ln(p) + 0.5] \cdot I_t \tag{4}$$

where v is wind speed (m/s), w walking speed (m/s), and p is clothing air permeability (mm/s).

2.4 Effects of Clothing on User

2.4.1 Thermal Balance and Microclimate

A human is a thermophysiologically tropical mammal, which means that the human body is homeothermic. Therefore an unclothed human's thermoneutral zone is relatively narrow and it is shown to be at air temperature between 25 and 30 °C (Erikson et al., 1956; Fourt and Hollies, 1970). Thermal balance depends on three main components: ambient conditions, clothing insulation, and metabolic heat production. In this study it was important to recognize forms of heat loss from the body that occur by conduction (contact with cold surface or liquid), convection (air or water movement), radiation and evaporation of sweat or water, and heat loss by respiration has a minor role. Human thermal balance is expressed in a heat balance equation (W or W/m^2):

$$M - W = E + R + C + K + S \tag{5}$$

where M is metabolic rate, W is mechanical work, E is heat transfer by evaporation, R is heat transfer by radiation, C is heat transfer by convection, K is heat transfer by conduction, and S is heat storage.

Human metabolic heat production can vary from 80 W to over 1000 W within average adult population (Parsons, 2002; Rossi, 2009). Use of PPC hinders heat and moisture transfer from the human body. When the body is in a thermoneutral state, S in the heat balance equation is 0. In cold conditions, cooling is a risk ($S < 0$), but on the other hand it is shown that use of PPC in the cold can even lead to heat strain ($S > 0$) if a strenuous workload is undertaken (Rintamäki and Rissanen, 2006).

Dynamic microclimate is formed around the worker by environment, clothing and body. The surrounding microclimate is called dynamic as there is constant heat and moisture exchange between those three factors (Pan, 2008). Umbach (1984) has determined that temperature of the air layer between clothing and skin should be between 30 and 33 °C and relative humidity less than 40% to maintain thermal comfort. On the other hand, higher relative humidity, such as 60 to 70%, can be acceptable for example in bed (Hänel and Holmér, 1986). Moisture accumulations in the clothing may cause critical cooling of the body, especially during resting periods following strenuous work – so-called post-exercise chill (Bartels and Umbach, 2002). Thus, moisture-handling properties may be critical for the user’s health in the cold.

2.4.2 Clothing Comfort

Statistics have shown that the most important clothing property for the users is wear comfort (Bartels, 2006), which has been recognized to consist of four different types of comfort: thermophysiological comfort, sensorial comfort, garment fit and psychological comfort (Holmér, 1989; Rossi, 2009).

Thermal comfort includes sensations of heat or cold as well as skin wetness. It is obtained when the feeling is not too cold nor too warm, and when the excess humidity from the body can be evacuated to the environment (Fanger, 1970; ISO 7730, 1984). It is shown that overall thermal sensation and comfort follow the coldest local sensation (hands and feet) in the cold (Arens et al., 2006). Evaporation of a wet inner layer causes cooling of the skin, and thus decreases thermal comfort (Bakkevig and Nielsen, 1994). Bakkevig and Nielsen (1995) reported that high intensity activity increased heat and sweat production leading to increased moisture accumulations in garments, and therefore greater thermal discomfort during work and resting period compared to lower work intensities.

Perception of comfort is also shown to be dependent on nonthermal factors (Holmér, 1989). Sensorial comfort detects sensations of the fabric feel near to the skin, such as prickling, itching, stiffness or smoothness. Sensorial comfort can be also affected by wet fabric which is shown to increase the friction between fabric and skin (Derler et al., 2007). Garment fit is considered as tightness and weight of the garments, and overall freedom of the movements of the user. Psychological comfort is formed by aesthetic properties, such as colour, construction, fashion, and suitability of the clothing for the occasion (Rossi, 2009).

2.4.3 Performance

Physical performance

Physical performance is negatively affected when core body temperatures are not between 36.5 °C and 37.5 °C. Lotens (1988) has collected a table of critical value physiological parameters using comfort, discomfort, performance decrement, tolerance and damage as criteria (Table 2).

Table 2**.** Approximate thermal strain criteria in the cold (Lotens, 1988).

Strain	**Comfort**	**Discomfort**	**Performance degradation**	**Tolerance**	**Damage**
Mean skin temperature (°C)	33	<31	30	25	<15
Rectal temperature (°C)	37	-	<36	<35	28
Heat loss (J/kg)	0	4	6	12	20

Cold protective clothing increases physical workload and energy expenditure by increasing energy consumption and heat production by 8–17% (Dorman and Havenith, 2009; Rintamäki, 2007). The weight of the clothing has the greatest influence, with its stiffness being the second most important factor. The weight increases energy consumption by 2.7% per clothing kilogram (Dorman and Havenith, 2009). Duggan (1988) has shown that heat production increased from 2.4 to 4.8% per clothing layer during stepping because of the weight of the clothing layers and friction between them. According to Nunneley (1989), increasing the effect of arctic clothing on oxygen consumption during treadmill walking was about 10% compared to tests with light clothing. As an example, fire fighters' standard protective gear strains the body about 40% more than light sports gear (Behman, 1984). It is studied that in Europe fire fighters need the gear only about 10% of their total active working time in service (Project Heroes, 2003).

Friction between the clothing layers and the effect of thick clothing in hindering the movement of the extremities add to the physical workload (Dorman and Havenith, 2009). Low friction coefficient is dependent on not only smooth surface but also fabric finishes that smooth the surface. Previous research (Anttonen et al., 1998b) found that friction between different dry fabric materials can vary by about 50%. The research showed that in a subject with low-friction clothing, physical performance was improved by from 7 to 13% and movement of extremities were 10% wider compared to high-friction clothing. Accumulated moisture in the fabric increases friction between clothing layers. To decrease friction of multi-layered clothing and thus effects on physical strain, low friction materials, such as polyamide and polyester, should be selected, e.g. as lining material of outermost clothing.

Manual performance

Manual performance in the cold is affected by cold temperatures, contact with cold surfaces, and the wearing of gloves (Bishu and Kim, 1995; Geng et al., 2006; Havenith et al., 1995). The lowest temperature to maintain practical bare-handed performance for more than a few minutes is reported to be −18 °C (Rogers and Noddin, 1984). Manual performance decreases in many ways due to cooling as presented in Table 3 (Enander, 1984). Although gloves greatly reduce the risk of hands cooling, they inevitably affect dexterity (Havenith et al., 1995). Peitso et al. (2003) showed that most of the winter military tasks (40–70%) were performed bare-handed due to the adverse effects of gloves on manual performance. Factors affecting finger and manual dexterity relate to glove material, such as its thickness, elasticity, deformability, as well as to the shape of the glove itself (EN 420+A1, 2009; Tanaka et al., 2010).

Table 3**.** Manual performance, function and perception at different skin temperatures (Enander, 1984).

Local hand skin temperature (ºC)	**Effects of temperature on manual function**
32–36	Optimal temperature
<32	Impairment of perception of roughness
27 (muscle)	Decrement of muscle power
20–27	Decrement in accuracy and endurance
13–18	Impairment of manual performance
12–16	Decrement in manual dexterity
16	Pain (whole hand cooling)
10	Pain (small area cooling)
8	Loss of tactile sensitivity
6−7	Loss of sensations
6	Nervous block
0… −2	Frost bite

Mental performance

Mental performance has a substantial impact on orientation, safety, decision-making, work efficiency and reactivity in demanding situations, and the physiological effects of cold exposure have a direct influence on mental performance. These effects can be seen even when no actual hypothermia can be diagnosed (Palinkas, 2001). Mäkinen et al. (2006a) showed that cold conditions decreased accuracy, but shorten reaction time leading to increased efficiency. They suggested that moderate cold exposure decreases cognitive performance due to distraction and having both positive and negative effect due to arousal caused by cold exposure.

Clothing properties and its model and materials affect perceived comfort and mental and cognitive performance (Bell et al., 2005). Sore studies are performed concerning effects of heat stress and fit on perception of clothing comfort and cognitive performance (Brooks and Parsons, 1999; Hancock and Vasmatzidis, 2003), but a limited number of studies is carried out concerning direct relationship between clothing comfort and cognitive performance. Bell et al. (2003) proved that reaction time and accuracy decreased when extremely uncomfortable clothing was worn.

2.5 Development of Cold Protective Clothing

The measure of clothing insulation, clo, was developed in the 1940s (Gagge et al., 1941), when also the first thermal manikins were created. Discussion on work clothing started at the end of the 1970s and international research on cold protective clothing, clothing physiology and thermal functions of clothing was started intensively in the 1980s. At this time also a number of scientific environmental ergonomics conferences addressed the specific problems of protective clothing and included sessions for clothing research (Holmér, 1989). In Finland clothing physiological research on protective clothing was intensified at the end of the 1970s by development of human size thermal manikin (Andersen, 1982).

Standardization of protective clothing, its requirements, measurement protocols and recommendations were launched in the 1990s. At the beginning of this millennium, the effects of cold protective clothing on thermoregulation and moisture transport in fabrics under cold climate were focused on. In addition, development of the research methodology for moisture exchange studies was concentrated in a more complex manner than previously, such as sweating hot-plates and torsos (Annaheim et al., 2015; Weder et al, 2008) and thermal manikins (Psikuta, 2009; Tamura, 2006), as well as modelling of clothing effects on human physiology and comfort (Holopainen, 2012). Modelling and calculation of utility ranges of the clothing systems created on individual selection of single garments is developed to predict safe working time outdoors.

Recently, the focus has been in measurement of human experiences and comfort perception during activities. Development of the portable measurement technology using wireless sensor technology and dataloggers is concentrated to enable more feasible measurement of human experiences as well as properties of the protective clothing. Nowadays, development of the cold protective clothing is considered as part of the risk management to support safe and healthy working as well as optimum selection is seen to improve perceived comfort, physical and mental performance due to clothing model, pattern and materials that take into account tasks, environmental conditions, and individual properties (Harlin and Norokorpi, 2011).

Working in extreme cold conditions demands for maximum thermal protection as well as changing physical activities easy adjustment of the level of thermal insulation. Auxiliary heat systems integrated into clothing have been developed to provide a solution for these conditions. Heated panels into the clothing can be based on electrical, infra-red or far infra-red heating (Jussila and Anttonen, 2011b; Jussila et al., 2013; Wang et al., 2010; Wang and Lee, 2010). It is shown that thermal comfort can be provided by additional heated systems (Brooks and Parsons, 1999). Heat can be conveyed in the textiles with conductive fibres, yarns or fabrics. Conductive materials are produced by integrating metallic wires into yarn or fabric, by coating fibres with metals or conductive films, or by adding conductive fillers (Ueng and Cheng, 2001). Research has also been carried out to develop cellulose based conductive materials (Acqua et al., 2004).

Material development of clothing for cold climate has been done to find lighter solutions with high thermal insulation properties. In addition, interactive materials have been developed, such as micro- and macro-capsulated phase change materials (PCM) (Bendkowska et al., 2010; Gao et al., 2010; Shim et al., 2001) and shape memory alloys (SMA) and polymers (Carosio and Monero, 2004; Lendlein and Kelch, 2002; Michalak and Krucinska, 2016). PCM are added into textiles to absorb heat energy when the temperature is rising and releasing heat when cooling. It has shown (Shim et al., 2001) that heat release by PCM in cold conditions reduce body heat loss by an average of 6.5 W with a one-layer suit and 13 W with a two-layer suit compared with a non-PCM suit. A limitation of PCM is that it provides temporary and relatively small heating/cooling effect when temperature changes. SMA are developed to return to a pre-determined form above a given transition temperature. These applications are used to change shape and thus for example increase automatically air content inside clothing when the temperature decreases (Michalak and Krucinska, 2016).

3 Materials and Methods

This chapter describes the studied materials and the used measurement facilities from fabric material testing to clothing measurements with thermal manikin and with human subjects in laboratory and in authentic field conditions in northern areas (Sodankylä, Finland) and in the offshore archipelago of the Gulf of Finland (Upinniemi, Finland). An overview on used multi-disciplinary methodology is presented in Figure 4.

Figure 4. Used testing material and methodology.

3.1 Materials

The measured materials in this thesis consisted of three-layered fabric combinations (Paper I), three (Paper II) and four-layered (Paper III) clothing combinations as well as different types of casualty coverings (Paper IV) and protective gloves (Paper V). The compilation of the variety of the analysed ensembles in this thesis is presented in Table 4. Detailed material descriptions are given in the original papers. The selected ensembles for the thesis were based on already existing products from the market or used by the outdoor occupations. The studied ensembles had different permeability, and they are categorized as permeable (PERM), semipermeable (SEMI) and impermeable (IMP), due to their fabric construction, used membranes, laminations or reflective layers, respectively.

All studied eight inner layer fabrics (Paper I) were measured together with a mid layer made of terry knit (WO 70% and PA 30%) and an outer layer made of weft satin weave (CO 50% and PES 50%). The used mid and outer fabrics were the same as those used in the field study presented (Paper III) in the newly developed military clothing model (M05).

The casualty coverings (Paper IV) were measured in the laboratory using a thermal manikin dressed in a long-sleeved shirt and long-legged underpants (PES 50%, CO 33%, MAC 17%), and calf length socks. Contrary to the original Paper IV, in this thesis only the impermeable ensembles that did not penetrate moisture through garment closures (bubble wrap, BW, and covering with aluminized foiled blanket, R2+RefB) were analysed and are presented in Table 4. In the field experiment, the selected casualty covering (R3) was worn together with layered winter clothing (LWC). Layered winter clothing (LWC) with rain clothing was used as control clothing (CC).

The effect of clothing size of the mid and outer layers on thermal insulation was measured in Paper II with three-layer clothing ensembles where the inner layer was in all cases the same size (small, S). The sizes of the mid and outer layers, and twelve size combinations of the measured clothing ensembles are presented in Table 5.

Table 4. Summary of used ensembles in this thesis. Type of ensemble: Fabric combination = F, Clothing = C, Gloves = G; Permeability: PERM = permeable, SEMI = semipermeable, IMP = impermeable

Paper	Code	Description	Layers	Type	Permeability
I	W1	Inner: PES 50%, CO 33% MAC 17%, rib knit	3	F	PERM
I	W2	Inner: PP 40%, CDM 30%, CO 30%, plush	3	F	PERM
I	W3	Inner: WO 46%, PP 42% PAN 12%, plush	3	F	PERM
I	W4	Inner: PA 95%, EL 5%, plush	3	F	PERM
I	W5	Inner: PES 100%, plush	3	F	PERM
I	W6	Inner: PES 100%, interlock	3	F	PERM
I	W7	Inner: PES 77%, WO 23%, 2-layer	3	F	PERM
I	W8	Inner: WO 100%	3	F	PERM
II	C1-C12	Inner: PES 66%, CV 29%, EL 5%, single knit; Mid: Microfleece PES 100%; Outer: 500D Invista Cordura®, Sinisalo® membrane; Filling and lining: 100% synthetic fibre	3	C	SEMI
III	M05	Inner: PES 50%, CO 33% MAC 17%, rib knit; Mid: terry knit shirt: WO 70%, PA 30% and trousers: WO 60%, PES 25%, PA 15%; Combat clothing: CO 50%, PES 50%, satin weave; Snow clothing: PES 70%, CO 30%, twill; Cold weather clothing: Outer fabric, PES 70%, CO 30%, twill and lining PES 100%	4	C	PERM
III	M91	Inner: PES 50%, CO 33% MAC 17%, rib knit; Mid: PA 80%, PES 20%, knitted fibre pile; Combat clothing: CO 65%, PES 35%, satin weave; Snow clothing: PES 70%, CO 30%, twill; Cold weather clothing: Outer fabric, PES 70%, CO 30%, twill and lining PES 100%, taffeta	4	C	PERM
III	Trad.	Inner: PES 50%, CO 33% MAC 17%, rib knit; Mid: PA 80%, PES 20%, knitted fibre pile; Combat clothing: WO 85%, PA 15%, felt; Snow clothing: PES 70%, CO 30%, twill; Cold weather clothing: Outer fabric, PES 70%, CO 30%, twill and lining PES 100%, taffeta	4	C	PERM
IV	1B	One blanket (PES 100%)	2	C	PERM
IV	2B	Two blankets (PES 100%)	2	C	PERM
IV	RescB	Medical fleece with micro porous membrane	2	C	SEMI
IV	R1	Medical fleece with micro porous membrane with integrated mattress	2	C	SEMI
IV	BW	Bubble wrap (PE 100%)	2	C	IMP
IV	R2+RefB	Thin cover with welt and integrated mattress and aluminized reflective blanket with honeycomb structure	2	C	IMP
IV	R3	Sleeping bag-like with zipper closure, PA 100% (sport nylon 210 denier), padding: 100% CO; lining: taffeta textile	2 & 5	C	IMP
IV	CC	Control clothing: T-shirt, long-legged underpants, turtleneck shirt, sweater (WO), mid pants, combat jacket and trousers, and cold-weather padded jacket and trousers, rain clothing. Feet: liner socks, felt linings, and winter rubber boots. Hands: leather gloves. Head: hat (WO)	5	C	IMP
V	G1	Leather / membrane / Nomex lining	1	G	SEMI
V	G2	Leather / Kevlar / membrane / PBI knit lining	1	G	SEMI
V	G3	Leather / textile	1	G	SEMI

Table 5. Sizes of the mid and outer layers, and size combinations of the measured clothing ensembles.

	Clothing size	
Code	**Mid layer**	**Outermost layer**
C1	XS	48
C2	XS	50
C3	XS	52
C4	XS	56
C5	M	48
C6	M	50
C7	M	52
C8	M	56
C9	XL	48
C10	XL	50
C11	XL	52
C12	XL	56

3.2 Clothing Physiological Measurements

The used testing methodology was based on clothing physiology, thermophysiology, usability of hand-held tools and subjective evaluation. The air temperature in the climatic chamber (Papers II, IV, V) was adjusted between −20.0 °C and +26.5 °C, and different wind speeds were selected as calm (0.3 m/s), moderate (4.0 m/s) and high (8.0 m/s). The wind was blowing horizontally from the front of the thermal manikin. The ambient temperature and wind speed were measured and recorded. The ambient conditions were controlled and calibrated regularly. The used methodology in this thesis is gathered in Table 6.

Table 6. Summary of used methodology in this thesis.

Category	Method	Property	Standard and reference	Paper
Fabric material testing	Hot-plate	Thermal resistance	SFS 5681: 1991, ISO 11092: 1993	I
	Sweating hot-plate	Evaporative heat loss	SFS 5681: 1991, ISO 11092: 1993	I
Clothing testing	Thermal manikin	Thermal insulation	EN 342: 2004, EN ISO 15831: 2004	II, IV
	Thermal manikin	Convective heat loss	Anttonen and Hiltunen, 2003	II, IV
	Thermal manikin	Pumping effect	EN 342: 2004, EN ISO 15831: 2004	II
	Thermal manikin	Evaporative heat loss	Goldman, 1981; Wang, 2011	I, IV
	3D body scanning	Air layer thickness and air gaps	Chen et al., 2004; Lee et al., 2007	II
Glove testing	Finger dexterity	Materials in the cold	EN 420 + A1: 2009	V
Required insulation	Calculation	IREQ and DLE indexes	EN ISO 11079: 2007	IV
Subjective evaluation	Questionnaire	Perceived comfort, coping, performance	EN ISO 10551: 2001	III
	Questionnaire and interviews	Thermal sensations	EN ISO 10551: 2001	III, IV
	Questionnaire and interviews	Moisture sensations	Wang et al., 2007	III
Physiological measurements	Telemetric thermo capsule	Core temperature	Rissanen, 1998	IV
	Thermistors	Skin temperatures	ISO 9886: 2004	IV
Micro climate and ambient conditions	Microtemp sensors	Relative humidity and temperature	Rissanen, 1998	IV
	iButton, portable loggers	Ambient temperature		IV
	Rotating vane anemometer	Wind speed		IV
Usability tests	Questionnaire	Visual analogue scale (VAS)	Beauchamp, 1999; Lintula and Nevala, 2006; Nevala and Tamminen-Peter, 2004; Toivonen et al., 2011	V

Dry thermal insulation and convective heat loss

Thermal insulation of the fabric material combinations was measured with a hot-plate supplied with guarding rings. Surface temperature was set to 35.0 °C and the measuring area was 0.0511 m^2. Temperature in the climatic box was selected to −15.0 °C and air velocity to 1.0 m/s. The repeatability of the test on the same specimens has shown to be about 7% when the thermal insulation is higher than 0.05 m^2K/W. The reproducibility based on an interlaboratory trial is reported to be an average standard deviation of 0.0065 m^2K/W (ISO 11092, 1993). Accuracy of the measured thermal resistance has been reported to be less than 5% (Anttonen, 1993).

The thermal insulation of the clothing ensembles was measured using an aluminium thermal manikin consisting of twenty segments located in a climatic chamber. The thermal manikin has the size of male person with a height of 176 cm and 1.89 m² body surface area. Surface temperature was set to 34.0 ± 0.1 °C. Thermal insulation was evaluated in different cases: standing (Paper II), dynamic (walking speed 0.51 m/s, 45 double steps/min, Paper II) and at a supine position on a steel plate (Paper IV).

The climatic chamber for the thermal manikin tests was set at ambient temperatures of +10.0 and −5.0 °C, and wind speeds of 0.3, 4.0 and 8.0 m/s. The effect of the direction of the wind at 8.0 m/s on thermal insulation was tested in Paper II by turning the thermal manikin to 0°, 45° and 90° angles to the wind. When the thermal manikin was turned 45° and 90° to the wind, the left side of the thermal manikin was facing the wind. Clothing ensemble C3 (Table 5) was used to determine the effect of the wind direction.

Calibration of the used equipment for the thermal manikin tests and climate control was performed according to the standards EN 342 (2004) and EN ISO 15831 (2004). The thermal manikin tests produce accurate and comparable results based on regularly performed accreditations in the laboratory. Therefore, one measurement per ensemble was performed. The reproducibility of the thermal insulation test results in a single laboratory has shown to be good and the coefficient of correlation being lower than 3% in standard conditions (Anttonen et al., 2004).

3D body scanning and air content determination

The influence of air content on thermal insulation was evaluated in Paper II. The undressed thermal manikin and each clothing layer in different sizes were scanned by a 3D body scanner using Human Solutions ScanWorX: Anthroscan software in wind speed of 0.3 m/s. The outer clothing layers were scanned also in wind speed of 8.0 m/s. A total of 31 scanned whole-body pictures were taken. Each separate 3D-scanned clothing layer was overlaid into one picture. In all of the whole-body pictures, the thermal manikin wore socks and boots. The hip of the thermal manikin was locked to give it a stable standing position. The simultaneous use of the method with the thermal manikin limited the ambient temperature to be at the lowest +10.0 °C.

To evaluate air layer thickness inside the clothing system, the body girth of each clothing layer and the thermal manikin were measured by 3D scanning system at five different points. From the scanned figures, cross-sectional measurements were made at five points: the chest (distance from the ground 133 cm), the waist (113 cm), the hip (94 cm), the thigh (72 cm), and the calf (39 cm). The measurement points were marked by tape to indicate the cross-sectional points on the thermal manikin and the different clothing layer surfaces. The thickness of the air layer (AG) between the clothing layers was calculated using the following equation (Chen et al., 2004):

$$AG = \frac{L_g - L_m}{7.14} - \frac{TH_m}{2}, \tag{6}$$

where AG is the thickness of the air layer (cm), L_g is the body girth of the upper garment (cm), L_m is the body girth of the manikin (cm), TH_m is the compressed thickness of fabric (cm), and constant 7.14 is the mean value of 2π and 8, as the real cross-section of the body girth is between a circular and rectangular shape.

The cross-sectional pictures of twelve clothing ensembles (C1–C12) were pooled into one picture illustrating the layered clothing system. The thickness of the air layers between the clothing layers was also estimated at ten sites from these pooled pictures by using the Anthroscan software. Total average values were also calculated at the front and back and both sides.

Wet thermal insulation and evaporative heat loss

Thermal insulation of the wet fabric combinations and heat loss from wet ensembles were determined in Paper I. The sweating hot-plate was used to measure required energy and time for moisture evaporation through fabric material combinations when water dosing was 300 g/m^2h during 1.5 hours which corresponded with hard physical work. The ambient temperature was set to −15.0 °C, and wind speed to 1.0 m/s.

The thermal manikin was used to study thermal insulation of the wet clothing combinations and heat loss from wet ensembles in Paper IV. The internal moisture effect on thermal insulation was evaluated by spraying 300 g of water evenly on the long-sleeved shirt and long-legged underpants before measurement started. This moisture input inside the ensembles corresponds with perspiration in medium level physical activity. An effect of external precipitation, such as rain and splashes, was simulated by sprinkling 2300 g of water on the upper surface of the covered thermal manikin. This corresponded with rainfall of 2 mm. The effect of the moisture on thermal insulation was monitored for four hours by thermal manikin. The ambient temperature was set in both experiments to −5 °C, and wind speed to 0.3 m/s.

The total heat loss (H_t in W/m^2) through the clothing systems was determined on the basis of total thermal insulation (I_t in m^{2}K/W) on clothed body area:

$$H_t = \frac{(T_{sk} - T_a)}{I_t} \tag{7}$$

3.3 Effects of Clothing on Thermal Comfort, Coping and Performance

Physiological measurements

Physiological parameters were measured in Paper IV. The core temperatures (T_c) of four healthy male test subjects were measured using a telemetric thermocapsule (Jonah™ Temperature Capsule, Respironics Inc. Murrysville, PA USA). The data was saved at one-minute intervals by data loggers (VitalSense® monitor IP52, Mini Mitter Company Inc., A Respironics Inc. Company, Bend, OR USA). Skin temperatures were measured at ten sites (cheek, chest, upper back, upper arm, hand, finger, thigh, calf, foot, toe) by thermistors (NTC DC95 Type 2252 OHM, Digi-Key, Thief River Falls, MN USA). The thermistors were fixed directly onto the skin by flexible tape (Fixomull stretch, BSN Medical GmbH & Co, Hamburg, Germany). The data were saved at one-minute intervals by data loggers (SmartReader Plus 8, ACR Systems, Surrey BC Canada). Weighted mean skin temperature (T_{sk}) was calculated according to ISO 9886 (2004) standard. In addition, relative humidity (Rh) and the temperature between the lower and mid layers were measured using a sensor (OM-CP-Microtemp, Omega, Laval, Quebec, Canada).

Questionnaire study

In Paper III were assessed the effects of the three cold protective clothing systems on human thermal and moisture sensation and on perceived physical and mental performance in long-term cold exposure during winter military training lasting eleven days. The participants were healthy, volunteered male conscripts, average age twenty years.

The clothing systems (M05, M91 and Trad.) were distributed at random. Ten subjects were wearing the M05 clothing, seven the M91 clothing and twelve the traditional clothing system. The clothing systems were not rotated between the participants for practical and hygienic reasons. Some variations to the garment combinations were made during the training by the users because of the weather and the activities. The data were analysed separately for the three compared clothing systems.

Two separate questionnaires, a clothing questionnaire and a surveillance card, were distributed in each training day. The total number of answers to the questionnaires was 319. The clothing questionnaire consisted of information on clothing variation during training, the coldest thermal and wettest moisture sensations in the different body parts and ease of use the mid layer, whereas the surveillance card was used to evaluate by 10-point scales the users' state of health, mental and physical performance, mood, motivation, stress level, nutrition and cold experiences. Finally, in this thesis the results were combined from the two questionnaires – from part of the clothing comfort consisting thermal and moisture sensations, and perceived physical and mental performance – to assess the significance of the used clothing.

Thermal (EN ISO 10551, 2001) and moisture (Wang et al., 2007) sensations were asked during experiments according to the scales presented in Table 7. The thermal sensation 'very hot' was left out as being irrelevant in these ambient conditions.

Table 7. Thermal (EN ISO 10551, 2001) and moisture sensation (Wang et al., 2007) scales used in the clothing questionnaire and in field measurements

Thermal sensation		**Moisture sensation**	
Very cold	0	Dry	0
Cold	1	Almost dry	1
Cool	2	Slightly moist	2
Slightly cool	3	Moist	3
Neutral	4	Almost wet	4
Slightly warm	5	Wet	5
Warm	6	Soaking wet	6
Hot	7		

Finger dexterity test with gloves

The finger dexterity tests with different gloves were performed in Paper V according to the standard EN 420+A1 (2009) with minor modifications: tests were conducted in both warm (+26.5 °C) and cold (−20.0 °C) conditions by one experienced tester according to the standard. Three right-hand gloves of each type were tested. The gloves were somewhat already used, i.e. not new. They were conditioned for 20 hours before measurements in test conditions.

The tests were performed with five centreless ground stainless steel test pins according to standard EN 420+A1 (2009). The tester picked up a pin by its circumference between his gloved forefinger and thumb without any other means of assistance (Figure 4). The tester was kept in thermal balance during the tests by sufficient clothing and by breaks between tests in warm conditions. The result value, i.e. level of performance corresponds to the smallest diameter of pin that was picked up according to the test procedure (EN 420+A1, 2009). The results were given as means (±SD) of each different glove type (n=3 per glove types).

Figure 5. Finger dexterity tests with different gloves using five test pins

Usability tests with different gloves

In Paper V was evaluated the usability of three different mobile phones used by rescue authorities with three different types of gloves and bare-handed in the cold. After the simulated communication tasks, modified visual analogue scales (VAS) were used to determine the usability features of the three different phone types (Beauchamp, 1999; Nevala and Tamminen-Peter, 2004; Lintula and Nevala, 2006; Toivonen et al., 2011). The VAS is a 100 mm long continuous line with endpoints anchored by 0 (very poor) and 100 (very good). The VAS score is a measured distance (expressed in millimeters) from the 0 scale point. The participants were asked to mark on the line the point that indicated their evaluation of the following features: fit for hand, the shape and weight of the phone, the placement of the tangent push-button, the shape of the push-buttons, the clarity and size of the screen, screen update in the cold, changing communication group, audibility of the speaking voice, volume control and compatibility of phone with gloves. In addition, an overall evaluation of the phones and overall functionality were carried out. The questions were prepared in co-operation with experienced rescue service professionals.

3.4 Statistics

In this thesis, the data (Papers I, III and V) were analysed statistically using the Statistical Package for the Social Sciences (SPSS) 15, 18 and 20 for Windows. The SPSS enabled direct analysis of each question and cross-tabulation of the data. The test subjects were given code numbers in the database, so that their identities were not revealed at any stage in the research. The data are presented as mean values and standard deviation (SD). The level of significance in all the statistical tests was taken to be $p<0.05$.

In addition to original Paper I, in this thesis Pearson's correlation coefficient was used to measure the strength of the association between the variables to each other. Due to small sample, one-way significance was used.

In Paper III, the independent samples t-test was used to test differences in the means for two clothing system groups in terms of thermal sensation, experience of external moisture and perspiration sensation and for physical and mental performance. The scale of thermal sensation (Table 7) was treated as continuous data according to standard EN ISO 10551 (2001). Percentage differences between the clothing systems were analysed using the χ^2 test, and differences in measured values in the surveillance data were assessed with an analysis of variance (ANOVA) with repeated measures.

In Paper V, the Shapiro-Wilk test was used to test the normality of the data. For normally distributed variables, the parametric One-way ANOVA was used, followed by Bonferroni post hoc tests to test the equality of the mean values of the VAS scores between each situation. For non-normally distributed variables, the Kruskall-Wallis, followed by the Mann-Whitney post hoc test, was used.

3.5 Analysis of Data

Analysis was based on the results presented in Papers I–V in response to the research questions and objectives presented in Table 1 in Chapter 1.2. A matrix between research questions and Papers I–V is presented in Table 8.

Table 8. Relation between research questions and Papers I–V.

Paper	RQ1 Role of inner layer	RQ2 Trapped air	RQ3 Moisture effects	RQ4 Wind effects	RQ5 Comfort, coping, performance	Findings for development
I	- Role of inner layer in cold protective clothing					- The most significant properties for design
II		- Evaluation of clothing size of 3-layer-clothing		- Effects of convective heat loss on effective thermal insulation - Influence of horizontal wind direction on vertical person		- Optimum clothing size in relation to thermal protection
III					- Perceived thermal comfort, coping and performance with different types of clothing	- Effect of different types of clothing combinations on user's experience
IV			- Effects of moisture evaporation due to internal and external moisture on thermal insulation	- Effects of convective heat loss on thermal insulation at supine position	- Physiological measurements of coping and thermal comfort	- Effects of the moisture from different sources on thermal properties - Effect of coverings on human thermo-physiological responses
V					- Usability of hand-held tools with different type of gloves in the cold - Effect of cold on finger dexterity	- Effect of cold on finger dexterity with different types of protection

4 Results and Discussion

This chapter summarizes the most significant results, discussions and findings made in Papers I−V in response to the research questions and objectives presented in Chapter 1.2.

4.1 Functionality of Inner Layer

Paper I answers the research question 1: *What are the most important clothing physiological functions of the inner layer as part of layered clothing to take into account under subzero temperature?* This paper compared and evaluated the thermal and moisture handling properties of eight different inner layer fabric materials combined together with a mid layer and outermost clothing fabrics measured with the sweating hot-plate under subzero temperature.

Moisture transfer from skin through textiles is a complex mechanism. Different studies in the literature have evaluated effects of inner layer materials, such as cotton, wool, polypropylene, and polyester, on human thermal responses (Ha et al., 1998 and 1996; Li et al., 1992). The inner layer is in contact with the skin, and a fabric is exposed to heat, water vapour and liquid exchange. Therefore, the aims of the inner layer are to keep the user's skin dry by wicking the moisture into the fabric, and transferring the moisture to the mid layer. Moreover, the inner layer that has sufficient moisture-handling properties and low moisture absorption energy from the skin provides the user’s dry moisture sensations and improved thermal comfort at work. Clarification of the most significant clothing physiological properties of inner layer materials as part of layered fabric combination is still needed for evaluation of the importance of inner layer material choice and differences between them in thermal and moisture transfer under subzero conditions.

Table 9 summarizes the most relevant results of the paper for this study and includes further analysed results of heat loss due to moisture effects. The energy (Wh) used for moisture drying was calculated in the Paper I and it is translated into heat content (kJ) for evaporation in Table 9.

Table 9. Properties of tested inner layer materials in three-layer fabric combination (T_a = −15 °C, wind speed of 1.0 m/s).

Code	**Thickness of inner layer fabric (mm)**	**Dry thermal insulation (m^2K/W)**	**Heat content for evaporation (90%) (kJ)**	**Drying time (90%) (min)**	**Heat loss from body (1.8 m^2) (W)**	**Change in thermal insulation when wet (%)**
W1 (PES/CO/MAC)	1.3**	0.272**	5.4	28	116**	−27
W2 (PP/CDM/CO)	1.0	0.253	7.2**	44	98	−24
W3 (WO/PP/PAN)	1.2	0.259	6.1	33	111	−26
W4 (PA/EL)	1.3**	0.258	3.6*	19*	114	−24
W5 (PES)	1.2	0.267	5.0	27	112	−28**
W6 (PES)	0.8*	0.251*	7.2**	45**	96	−26
W7 (PES/WO)	1.0	0.260	5.0	39	78*	−26
W8 (WO)	1.0	0.255	4.0	22	108	−22*

** lowest value, ** highest value*

The results showed that changing the inner layer material in the three-layer fabric combination changed the dry thermal insulation in relation to material thickness (Pearson's correlation coefficient r = 0.74, $p<0.05$). However, the difference between the lowest and the highest value was about 8% being 0.02 m^2K/W. Thickness of the fabrics was greatly influenced by fabric construction if it was made from e.g. plush, single or rib knit. The thickness of the inner layer as part of two-layer clothing is shown to have more influence on the thermoregulatory responses and thermal comfort than the type of the fibre (Bakkevig and Nielsen, 1994).

The functional mechanism of the inner layer material as part of three-layer combination was especially seen in variation in heat content for moisture evaporation through ensembles until 90% of the steady state value. The heat content had significant relation to drying time until 90% of the steady state value (r = 0.90, $p<0.001$). The drying time was related to thickness of the inner layer material (r = −0.71, $p<0.05$) as it was expected based on earlier studies (Laing et al., 2007). In this study, both heat content for evaporation and drying time were the lowest with the ensembles made from polyamide (W4, thickness 1.3 mm) and wool (W8, thickness 1.0 mm). However, the thinnest fabric made of polyester (W6, thickness 0.8 mm) had the highest heat content for evaporation and the longest drying time. This ensemble had dense interlock fabric construction that may hinder moisture transport through the fabric. Short drying time could indicate that water molecules do not bind into the fibre structure, and therefore heat content for evaporation and decrease in thermal insulation remained low.

The results of the study showed that the inner layer material influenced on decrease in thermal insulation when wet by 6%. The decrease of the thermal insulation caused by simulated perspiration was the lowest with the woollen ensemble (W8). Variation in moisture accumulations in the inner layer fabric ensembles was narrow. About 1–4% of the total moisture input was accumulated in the inner fabrics. On the other hand, previously it has been suggested that the influence of inner layer fibre material on distribution of moisture accumulations, thermo-physiological responses and subjective sensations is more evident when sweating rate is higher (Bakkevig and Nielsen, 1995; Rissanen et al., 1994). In this study, simulated perspiration (150 g/m^2h) corresponded with moderate physical activity and the moisture was able to transfer through the ensembles contrary to higher sweating rate and, therefore, fibre type did not have as high an impact on moisture accumulations.

In this thesis was calculated heat loss corresponding with average human body size (surface area 1.8 m^2) using heat content for evaporation and drying time (Table 9). The heat loss was statistically related to thickness of the inner layer fabric ($r = 0.70$, $p<0.05$) and drying time ($r = -0.69$, $p<0.05$). The difference in heat loss between the highest (polyester, cotton and modacrylic) and lowest (polyester and wool) was 38 W, which corresponds with 15% of heat produced while walking (4–5 km/h) or almost half of the basal metabolic rate (Ainsworth et al., 2000). The source for evaporative heat loss of the inner layer is the skin. When the moisture is transferred to the next clothing layer, direct cooling of the skin does not occur. In practice, the influence of the heat loss from different inner fabrics would be the greatest after high physical work causing an intensive ‘after cooling’ effect.

The results suggest that the inner layer fabric made of wool or polyamide had the lowest heat content for moisture evaporation, the shortest drying time and the lowest decrease in thermal insulation when wet. The thermal insulation was shown to be more affected by fabric thickness and construction of the inner fabric than fibre material. When moisture is absorbed into the inner fabric, heat is released due to exothermic reaction which from wool is about 2.5 times higher than that released from polyamide (Hänel and Holmér, 1986). Therefore, wool feels warm and also dry (Hänel and Holmér, 1986) even when it has absorbed moisture. Based on their physical structure, woollen garments are expected to have higher thermal insulation due to higher air content in the fibre, yarn and fabric. Wool fibre is a naturally crimped, flexible and breathable material. In addition, felting of the wool inner fabric can be prevented by finishing treatments, leading to shorter drying times (Laing, 2009).

This study was performed using the sweating hot-plate method for fabric combinations. This method is evaluated as suitable for analyzing differences of the textile materials and moisture transfer mechanism (Anttonen, 1993). Effects of the inner layer material on human responses have been found in heart rate, core and skin temperatures, heat content of the body, humidity under garments and time to onset sweating (Laing et al., 2008; Wang et al., 2007). Future studies taking into account both thermal and sensorial comfort sensations with different types of inner layers should be performed. These sensations are expected to be affected by material wicking and moisture handling properties.

Summary and future perspectives

The thermal and moisture handling properties of the eight inner layer fabrics together with mid layer and outermost fabrics were studied under subzero temperature. It was found that the most important functions of the inner layer as part of layered fabric combination were moisture handling properties, such as heat content for evaporation (the highest 100% greater than the lowest), drying time (difference 26 min), heat loss (difference 38 W) and decrease in thermal insulation when wet (difference 6%). According to the results, woollen inner layer provided suitable thermal and moisture handling properties for cold climate. Modern finishing methods improve natural features and maintenance properties of the woollen fabrics e.g. by prevent felting during washes. As expected, thermal insulation was seen to be related to fabric thickness, and it did not vary strongly between the studied inner layer ensembles. Practically, the effects of different types of inner layer can be seen especially after heavy work period in the intensity of the ‘after cooling’ effect, which is diminished by correct material selection.

Moisture transfer through fabric layers in low ambient temperatures is a complex process. Apart from fibre material, also fabric construction and density and their influence on moisture transportation through fabrics should be considered. The inner clothing layer is in direct contact with the skin, and therefore it has great influence except on thermal but also sensorial comfort. These comfort sensations are affected by clothing physiological properties but also by fibre characters, such as fibre diameter and length, fabric construction and their finishes. In future studies, these aspects should be considered in cold climate and taken into account from the holistic point of view as part of comfort and well-being at work.

4.2 Size optimization of Layered Cold Protective Clothing

Paper II answers research question 2: *How does the size of the different clothing layers affect dry heat transfer in static and dynamic situations?* The Paper concentrates on analysing in detail the effects of different clothing layer sizes and air layer thicknesses between the layers under cool temperature (+10 °C) and in calm wind speed of 0.3 m/s and strong 8.0 m/s using a stationary and dynamic (walking speed 0.51 m/s, 45 double steps/min) thermal manikin. The effects of different materials and fabric constructions on the effective thermal insulation were eliminated by using the same materials in each clothing ensemble.

To analyse relative changes in the intrinsic clothing insulation of the different clothing layer sizes, the effective thermal insulation (I_{cle}) and the resultant effective thermal insulation (I_{cler}) without the surrounding insulating boundary air layer were used. The literature explains that total thermal insulation (I_t) highly decreases in windy conditions due to the breakdown of the boundary air layer around the clothing surface (Havenith et al., 1990b; Holmér et al., 2001). The thermal insulation of the boundary air layer (I_a) in calm conditions (0.3 m/s) with the static thermal manikin was on average about 16% of the I_t and about 19% with the dynamic thermal manikin. Hänel and Holmér (1986) have presented that the I_a varies from 0.03 to 0.12 m^2K/W depending on wind speed, which corresponded well with the values here in calm conditions.

The study indicated in outline that tight clothing provided on average about 17% lower effective thermal insulation (I_{cle}) in calm (0.3 m/s) and 13% in windy conditions (8 m/s) than loose-fitting clothing. This corresponds well with the literature that tight clothing fit has 6–32% lower insulation than loose-fitting clothing in wind speeds of 0.5−2 m/s (Chen et al., 2004; Havenith et al., 1990b; Lee et al., 2007). This effect is remarkable considering that the relative difference calculated between the total thermal insulation (I_t) of three different four-layered clothing systems used in the Paper III was about 8%. This relative difference was formed by variation of clothing materials and the clothing sizes were the same.

On the basis of this study, the I_{cle} of the ensembles in calm and windy conditions using both the static and dynamic thermal manikin tended to be higher when the outermost clothing layer was larger and formed a thicker insulating air layer under the clothing system. The medium size mid layer provided the highest thermal insulation values in the wind and with dynamic movement. Locally, the cusp of the effective thermal insulation of different clothing sizes was more visible when wind or movement were present as illustrated on a torso with medium size mid layer in Figure 6.

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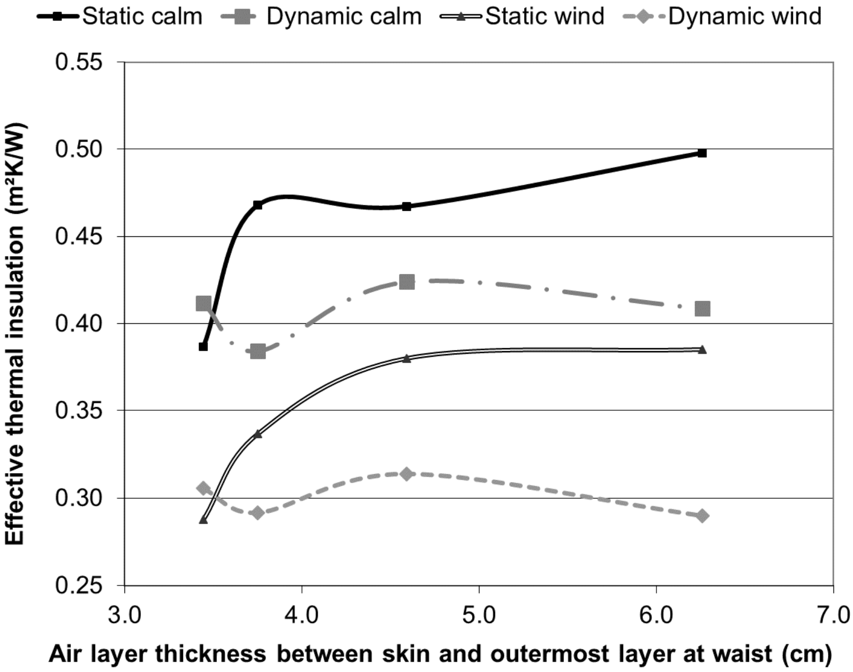

Figure 6. Effective thermal insulation (I_{cle}) on torso with medium size mid layer in relation to distance from inner surface of outermost garment to skin at waist (reproduced from Paper II with permission)

In Figure 6 be seen two different shapes of the curves, one for the static and one for the dynamic situation. In the static cases, including both calm and windy conditions, the measured I_{cle} tended to be higher when the outermost garment was larger, but in wind the I_{cle} reached its highest value and did not indicate tendency of further increase. In static situations, the thermal insulation was on average about 0.13 m^2K/W per centimetre of thickness when the I_{cle} was divided by air layer thickness between skin and outermost layer. Moreover, the I_{cle} increased about 0.03 m^2K/W per centimetre of air according to linear increase of thickness due to higher air content inside the clothing. In earlier literature, an increase of thermal insulation about 0.29 m^2K/W per centimeter of thickness has been presented (Fourt and Hollies, 1970). This value from literature was measured with flat fabric combinations, and therefore does not provide comparable value with three dimensional clothing with curvature structure and moderate air movement inside the clothing. Also should be recognized that heat loss increases when the larger outer garments are used due to higher outer surface, but the same time thermal insulation increases due to higher air content inside the clothing. Therefore, the seen effects in the static conditions are based on combination of these two factors.

The second curve shape in Figure 6 was in the dynamic situations, where the highest cusp of the I_{cler} was found when the distance from inner surface of outermost garment to skin was 4.7 cm. The

I_{cler} was lower whether wind speed was 0.3 or 8 m/s, if the garment size was larger or smaller than at the cusp. Also, higher I_{cler} was seen with the smallest outer garment, when the pumping effect due to walking was diminished due to thin air layers inside the clothing.

These results showed that the relative effect of the wind was locally greatest on the chest when the outermost clothing was the smallest in size, due to almost total compression of the air layers underneath the clothing system. In contrast, when the clothing size was the largest, the relative effect of the wind increased due to convective heat loss by ‘chimney effect’ (Fanger, 1970). The effects of the wind on cold protective clothing is discussed in more detailed in Chapter 4.4.

In the study was presented that the movement of the thermal manikin decreased the effective thermal insulation by 12−22% and the total thermal insulation by 9−19% depending the outermost clothing size. The relative effect of body movement (i.e. by pumping) was higher in calm than in windy conditions when the two smallest outermost clothing sizes were used, whereas the relative effect of the movement was greater in wind with the two largest outermost garments. In addition, the relative effect of pumping was the highest when the largest outermost garments were used. Anttonen and Hiltunen (2003) found that movement of thermal manikin (0.3−0.8 m/s) decreased total thermal insulation of layered clothing by 10−20%, whereas elsewhere have been found effects of 30−35% due to higher walking speeds (>0.8 m/s) (Havenith et al., 1990b; Olesen and Nielsen, 1983).

In the literature, Nilsson et al. (2000) have originally presented the equation (Equation 4) to calculate the effects of wind and movement on the total thermal insulation of the cold weather clothing. When the effect of walking in calm wind speed (0.3 m/s) is calculated, the relative decrease in thermal insulation (mean about −4 ± 0.0%) was remarkably less than the measured decrease (mean about −16 ± 3.4%). On the other hand, the equation provided accurate estimation on effects of wind and movement in higher wind speed (8 m/s) comparing to measured values, the mean decrease being about −35% (± 0.0) and −38% (± 3.4) calculated and measured, respectively. The measured values revealed variation in effects of wind and movement between different clothing size combinations contrary to the equation. It was seen that the relative decrease in thermal insulation was the highest when outermost garments were the largest, whereas the equation did not take into account the clothing size and thus amount of air content inside the clothing. Therefore, the calculated standard variation of the relative decrease in total thermal insulation did not exist.

Inside the clothing system, the mid layer between the close-fitted inner layer and the outermost layer divides the air content into two separate air layers. The medium size mid layer provided higher I_{cle} than the other mid-layer sizes on the torso. This indicates that a tight-fitting mid layer creates a thick air layer between the mid- and outermost layers, in contrast to a loose fit between the mid- and inner layers. An excessively thick air layer underneath outermost layer increases convection and the pumping effect under the clothing. The 3D scanned pictures showed that the wind of 8.0 m/s compressed air layers underneath the clothing, thus leading to a decrease in the effective thermal insulation.

The clothing size of the thermal manikin was M or between 48 and 50, based on the girth measures of the chest and waist when comparing to the European standard on size designation of clothes (EN 13402–3: 2004) and national Finnish guidelines (Finatex, 1988). The medium (M) size mid layer provided the highest effective thermal insulation values on the torso in wind and with dynamic movement, whereas outermost clothing size 52 provided the highest values and had the smallest relative effect on torso caused by wind on the upper body in static situations. The selected base layer size was tight-fitting in all the ensembles, and thus no space for air layer between body and inner layer existed. In the study, the outermost garment of size 52 had about a 35 cm difference (40% larger than body) in waist girth and the distance from inner surface of outer layer was 4.7 cm. A size M mid layer had about an 18 cm difference (20% larger than body) in waist girth. Air layer thickness between each garment layer was possible to calculate using Equation 6, which extracts the thickness of the fabric. This revealed that the air layer thicknesses were about 2.2 cm and 2.4 cm between inner-mid layers and mid-outer layers, respectively. The mid layer divided air content inside the clothing into two halves between inner and outer layers, when the inner layer was tight fitted. It was stated earlier in this chapter that one centimetre of increased amount of air raised the effective thermal insulation by 0.03 m^2K/W. Thus, these optimum air layers inside the clothing provide insulation of about 0.14 m^2K/W corresponding with one additional clothing layer.

The air layer thicknesses in the layered arctic clothing have formerly been proposed to be about 0.5 cm between the garment layers, having in total thickness of air 2.6 cm inside the five-layer clothing (Fourt and Hollies, 1970). More recently has been shown that the highest thermal insulation value of one-layer clothing was obtained when the thickness of the air layer was 1 cm (corresponding to 7.5 cm difference in girth) in calm conditions and 0.6 cm (corresponding to 5 cm difference in girth) in wind at a speed of 2 m/s (Chen et al., 2004). Lee et al. (2007) proposed that with two-layered clothing to obtain the highest thermal insulation value without cooling effect by ventilation was provided by a difference of 2.3 cm in radius on chest between body and outer garment. In this thesis, the difference in girth values were considerably larger and calculated distance from body to outer garment was about double compared to the most recent literature because of higher number of clothing layers. Two clothing layers inside the outermost layer forms air sections underneath the clothing, and thus three-layer clothing prevents air movement and ventilation inside the clothing more than single-layered clothing. This suggests the optimum clothing size of the outer layer to be larger with higher air content than has been proposed in earlier literature.

In this chapter was considered that still air content inside the clothing should be taken into account as one of the raw materials of cold protective clothing. The optimum amount of air inside the clothing provides close to an intrinsic insulation of one clothing layer. It was determined that the optimum outermost garment size providing the highest thermal insulation in wind with movement was one size larger than suggested in the European standard and recommendations for clothing size, even; the relative effect of the wind and movement was the higher with the larger garment sizes. This suggests that the one-size greater girth measures should be applied when designing and patterning cold protective clothing, and this should be considered in European standards for clothing size (EN 13402-3) in cold climate. These results should be also considered in the standard for cold protective clothing (EN 342), as the clothing size affects evaluation of thermal insulation by thermal manikin, and the equation for corrected value of thermal insulation in wind while walking does not take into account the effect of clothing size.

The used 3D methodology enabled precise determination of the optimum size of different clothing layers, their looseness values in girth and air layer thicknesses inside three-layered winter clothing. The optimum air layer thicknesses being about 2.3 cm at waist, when the inner layer was snugged onto skin and the mid layer divided the air gap into two sections with the same thickness. A similar idea of capturing still air is used already in material design e.g. in bubble wrap and 3D fabric materials and in hollow fibre materials. Varying the mid and outermost garment sizes saw even higher relative differences in the effective thermal insulation than when varying material choices of a layered clothing system. This is already taken into account in the construction industry when designing insulation of buildings and windows in cold climate regions. In future studies of cold protective clothing, already existing technologies, e.g. from the construction industry, or smartly adjustable sections for still air, could be developed based on biomimetics and shape memory alloys.

4.3 Moisture Impact on Heat Loss from Clothing

Research question 3 is answered in Paper IV: *How does moisture from internal and external sources affect heat transfer through clothing under subzero temperature?* This paper concentrates on analysing effects of moisture from internal and external sources on dry thermal insulation of the prehospital casualty coverings and heat loss from them in the below-zero temperatures. The ensembles had different permeability, and they are categorized in this thesis as permeable (PERM), semipermeable (SEMI) and impermeable (IMP), due to their fabric construction, used membranes, laminations or reflective layers, respectively. The most common source for internal moisture inside work wear is sweating, but, for example in the case of prehospital covering, it may also occur due to wet clothing or bleeding, whereas the external moisture appears due to rain, water splashes, wet ground, snow or sleet. The external moisture may penetrate also into semipermeable or impermeable materials through a semipermeable membrane, and garment closures, such as zippers or seams.

In design and development of cold protective clothing it is required to consider that moisture has dramatic effects on heat loss in the cold ambient temperatures and decrement of the thermal insulation by condensed moisture in the textile materials due to increased conductivity, decreased amount of insulating air and compression of thick materials. Therefore, in this thesis is clarified the effects of moisture under subzero conditions on dry and wet heat transfer through different material types and permeabilities. Especially, new information on influence of external moisture on thermal insulation and heat transfer below zero degrees is produced.

Thermal insulation of wet clothing

Thermal insulation, heat loss and permeability categorization of the studied ensembles when dry are presented in Table 10. Contrary to the original study, in this chapter only the impermeable ensembles which did not penetrate moisture through garment closures (bubble wrap and covering with aluminized foiled blanket) were analysed.

Table 10. Thermal insulation, heat loss and permeability categories (permeable=PERM, semipermeable=SEMI, impermeable=IMP) of different coverings when dry in wind speed of 0.3 m/s.

Code	Thermal insulation (m^2K/W)	Heat loss (W/m^2)	Permeability category
1B	0.35	112	PERM
2B	0.50	79	PERM
RescB	0.32	122	SEMI
R1	0.44	88	SEMI
BW	0.26	150	IMP
R2+RefB	0.80	49	IMP

Decrement of the thermal insulation was seen when the moisture took place in the textile materials despite the source of the moisture. Figure 7 is upgraded from the used data in Paper IV, and it illustrates the mean relative effects of the internal moisture (sprayed 300 g of water on inner layer) and externally sprinkled water (2300 g) on dry thermal insulation of permeable (PERM, n=2), semipermeable (SEMI, n=2) and impermeable (IMP, n=2) ensembles. After sprinkling the external water on the ensembles, the amount of unabsorbed water drippage varied from 606g to 1901g, depending on the moisture permeability of the outer layers.

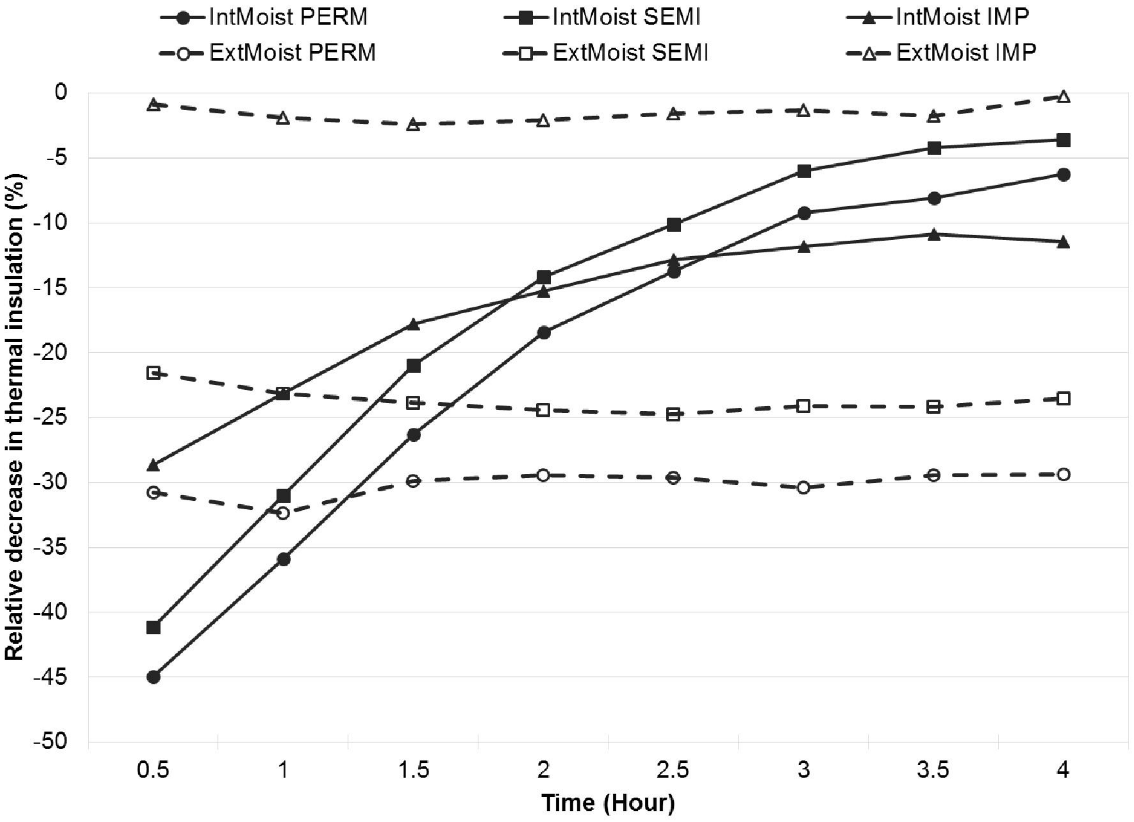

Figure 7. Mean relative decrease (%) of dry thermal insulation of permeable (PERM, n=2), semipermeable (SEMI, n=2) and impermeable (IMP, n=2) ensembles during four-hour measurement due to internal moisture (sprayed water 300 g) and external moisture (sprinkled water 2300 g, absorbed 400−1700 g) at ambient temperatures of −5 °C, and wind speed of 0.3 m/s.

In Figure 7 can be seen a clear difference in influence of wet thermal insulation depending whether the moisture occurred from an internal or an external source. In case of internal moisture, the relative change in thermal insulation recovered during the measurement referring to moisture evaporation and drying of the ensembles, whereas exposed to external moisture the relative change remained the same during the measurement under subzero temperature. The relative decrease in thermal insulation due to external moisture had different levels depending on permeability of the ensembles and, thus, in moisture penetration into the ensembles. However, absorbed external moisture into the ensembles caused a 15–30% lower immediate decrease in thermal insulation depending on the material permeability than internal moisture exposure caused, but the decrement stayed stable until the end of the measurements.

Exposure to internal moisture decreased dry thermal insulation of the ensembles by 22−46% due to moisture transfer from inner garments to the outer fabrics after thirty minutes of spraying the water (Figure 7). After that, moisture evaporation through outer fabrics occurred and the thermal insulation started to recover. After four hours, the relative effect of moisture on ensembles varied from 0 to 23%. The mean standard deviation of the relative decrease in thermal insulation was 4, 4 and 15% for PERM, SEMI and IMP ensembles, respectively. Impermeable layers prevented the moisture evaporation through the fabric and they had on average the lowest relative decrease of the thermal insulation after thirty minutes (Figure 7), and the recovery was the slowest with these ensembles. Moisture evaporation from impermeable materials was possible to occur only through garment openings by the ‘chimney effect’, whereas permeable and semipermeable ensembles allowed moisture evaporation also through the fabrics. When moisture vapour reaches the outer barrier layer, it condenses into textile materials and increases the conductivity of clothing layers. Chen et al. (2003) suggested in their study that users’ cooling effect after sweating is not caused only by the heat absorption due to the desorption and evaporation of moisture within the clothing, but also by reduced thermal insulation. They considered that this is not commonly taken into consideration, and the relative decrease especially with impermeable materials is high after long periods in the cold.

The mean relative decrease due to external moisture on the I_t of the ensembles (Figure 7) was not as strong (0−39%) as the effect of the internal moisture at thirty minutes after water sprinkling, even though the amount of water remaining on and inside the ensembles (about 400−1700 g) was higher than the amount of internal moisture (300 g). The mean standard deviation of the relative decrease in thermal insulation was 16, 14 and 11% for PERM, SEMI and IMP ensembles, respectively. The moisture penetration into the coverings continued until after one hour from the water sprinkling, and it was seen in minor reduction in thermal insulation at this time. Contrary to effects of the internal moisture, the I_t of all the measured ensembles in the original study remained almost the same (relative effect 0−30%) until the end of the measurement (four hours). The I_t remained at original, dry level throughout the measurement, when the outermost layer was impermeable and the water did not pass through the seams or other functional details of the ensemble (Figure 7), such as bubble wrap or covering with aluminized foiled blanket.

Exposure to external moisture at subzero ambient temperatures is assumed to cause formation of ice on the clothing surface and thus prevents evaporation and transfer of the absorbed moisture to the environment. Theoretically, ice formation occurs when the intrinsic insulation (I_{cle}) would be at least 0.78 m^2K/W if calculated by modified Equation 2, where heat loss (H) through clothing and the surface area (A) are considered to be the same for the intrinsic and total thermal insulation

$((T_{sk}-T_a)/(I_{cle}+I_a) = (T_{sk}-T_{Surface})/I_{cle})$. This was resulted in order that clothing surface temperature ($T_{Surface}$) was 0 °C and other parameters from the test procedure of this thesis were used (T_{sk} = 34 °C, T_a = −5 °C, I_a = 0.115 m²K/W). This calculated intrinsic insulation is higher than the measured insulation of the ensembles, in which case ice formation should not occur. However, in practice visible ice formation occurred especially locally on the parts that were covering the legs and arms. This can be explained by smaller volume of the warm body parts inside the sleeping bag type coverings.

Moisture Accumulations

The study resulted that due to internal moisture an average 89% of the water from the inner clothing had evaporated through permeable and semipermeable ensembles four hours after the test began. In contrast, an average 45% of the moisture was evaporated through the impermeable ensembles. According to Richards et al. (2008) the condensed moisture into different garment layers is strongly dependent on water vapour permeability of the outer layer and moisture from impermeable ensembles is able to evaporate through garment openings (20%), such as a collar.

It was found that the thermal insulation remained more or less the same throughout the measurement after sprinkling the external water on the ensembles. However, an average 40% (560 g) of the remained water on or inside the PERM and SEMI ensembles, and an average 63% (420 g) through the IMP ensembles was expired during the tests. The penetrated moisture condensed into the outer layers increasing conductivity of the materials. The relative effect of external moisture on the I_t of permeable materials was higher because the amount of penetrated moisture was greater than into semipermeable and impermeable materials. Some amount of water remained and may cause ice formation outside the ensembles in subzero temperature. This transformed the permeable materials to impermeable. Therefore, in this case heat loss mechanisms from permeable, and also from semipermeable, materials were similar to impermeable materials and evaporation was possible only through garment openings.

Accumulated water in clothing increases along with increasing sweating rate and declining ambient temperature (Bartels and Umbach, 2002; Meinander and Hellsten, 2004). These excessive moisture accumulations during high activity working in subzero temperatures deteriorate thermal comfort and cause harmful cooling after the activity. Therefore, ventilation systems should be improved inside the clothing. Biomimetics is imitating properties and transferring ideas from biology to technical solutions, and it could provide a smart solution by adaptive insulation and ventilation. Heat control of penguins and how they survive in extreme conditions has been studied, for example by Dawson et al. (1999) and Du et al. (2007). The penguin coat is formed by feathers and afterfeathers that provides highly efficient insulation and excellent barrier against wind as well as it transforms into a waterproof layer eliminating trapped air when diving under water. Based on biomimetics, it is already created adaptive insulating material by variable geometry textiles. A similar effect has been also produced by shape memory alloys (SMA) to increase air space when temperature changes and thus raise the thermal resistance (Kapsali, 2009). These mechanisms could be modified for increased ventilation system as well by providing free air movement inside formed ventilation “pipe lines”.

Dry and evaporative heat loss from wet clothing

In addition to published results, in Paper IV can be discussed the effects of the internal and external moisture on heat transfer through the ensembles under subzero temperature on the basis of the dry and evaporative heat loss. Havenith et al. (2008) have studied that evaporative heat loss is increased when clothing becomes wet, but the evaporative heat loss on the basis of mass loss (E_{mass}) from a clothed person does not always represent the total evaporative heat loss. Therefore, they evaluated apparent evaporative heat loss (E_{app}) by calculating the difference between the total heat loss from wet clothing (H_{t_wet}) and the total dry heat loss (H_{t_dry}). The apparent evaporative heat loss (E_{app}) includes also heat transfer mechanisms of wet conduction and evaporation-condensation.

When these calculation methods are applied to the results of this thesis, the total heat loss calculated using Equation 7 from the wet ensembles (H_{t_wet}) due to internal moisture was the highest after thirty minutes, averaging about 161 W/m² (± 48, SD), and decreased during the measurement, being at the end of the measurement on average 106 W/m² (± 31), whereas the total heat loss was the same after exposure to external moisture being on average about 123 W/m² (± 46) and 121 W/m² (± 39) after thirty minutes and four hours, respectively. The total heat loss from dry and wet ensembles after 0.5 and 4 hours is illustrated in Figure 8. This corresponds with phenomenon seen in recovery of thermal insulation presented in Figure 7.

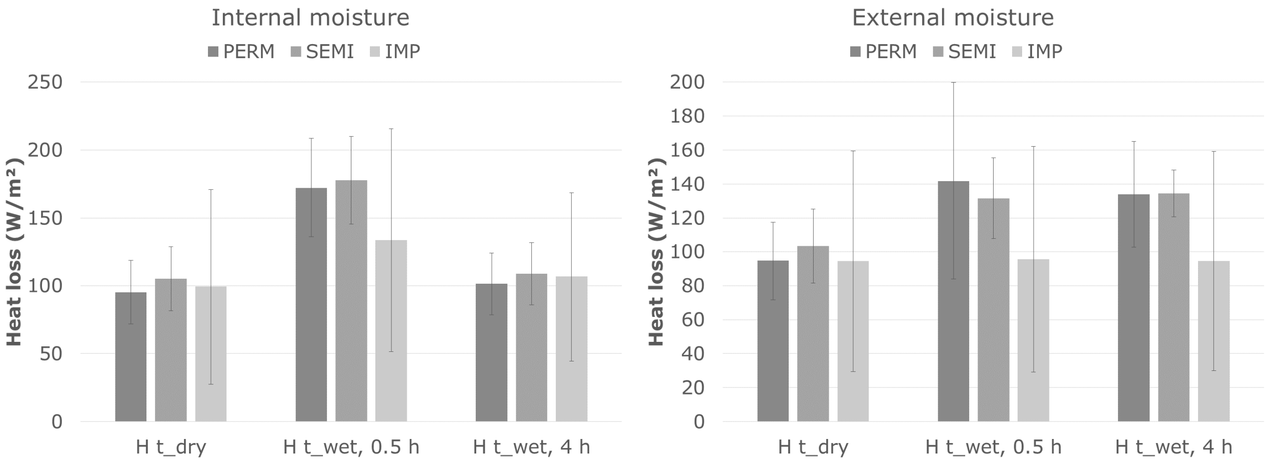

Figure 8. Total heat loss (±SD) from dry and wet permeable (PERM, n=2), semipermeable (SEMI, n=2) and impermeable (IMP, n=2) ensembles after 0.5 and 4 hours due to internal moisture (sprayed water 300 g) and external moisture (sprinkled water 2300 g, absorbed 400−1700 g) at ambient temperatures of −5 °C, and wind speed of 0.3 m/s.

Havenith et al. (2008) reported that the apparent evaporative heat loss (E_{app}) was about 45−60% of the total heat loss at ambient temperature +10 °C, and it increased in higher ambient temperatures due to diminished dry heat loss by the decreased temperature gradient between skin and ambient air. Using the results of this study for the calculation, the apparent evaporative heat loss (E_{app}) due to internal moisture averaged about 43% (75 W/m²) of the total heat loss from the PERM and the SEMI ensembles, and about 29% (34 W/m²) from the IMP after thirty minutes. As assumed, the values are lower than presented in the literature due to lower ambient temperature (−5 °C). In addition to dry and evaporative heat loss, a third form of heat loss due to cycle of evaporation and condensation of moisture is reported to exist in the cold (+10 °C) when exposed to internal moisture. This additional heat loss is increased in impermeable clothing, being about 45% of the total heat loss (Richards et al. 2008). More cycles of moisture absorption-desorption can be expected on its way to the ambient due to the higher microclimate water vapour pressures when permeability of the clothing is lower (Havenith, 2002a; Havenith et al., 2004).

When exposed to external moisture, the total dry heat loss (H_{t_dry}) was higher, and averaged about 82% (± 15) of the total heat loss from wet clothing (H_{t_wet}), than the apparent evaporative heat loss (E_{app}) during the measurement. The apparent evaporative heat loss (E_{app}) due to external moisture averaged about 26% (38 W/m²) of the total heat loss from the PERM and the SEMI ensembles, and only about 1% (15 W/m²) from the IMP after thirty minutes. The apparent evaporative heat loss (E_{app}) was lower when exposed to external moisture (on average about 25 W/m²) than to internal moisture (on average about 61 W/m²), because moisture penetrated into outer fabric layers and increased conductivity of the materials, but the cycle of moisture evaporation and condensation inside the ensembles did not occur. When the outermost layer was impermeable and the water did not pass through the seams or other functional details, also the apparent evaporative heat loss (E_{app}) was minimal or it did not exist.

Summary and future perspectives

In this chapter was clarified moisture impact from internal and external sources on the clothing thermal insulation and mechanisms of evaporative heat transfer under subzero temperatures. Especially, effects of the external moisture in these ambient conditions are not thoroughly reported. It was found that immediate decrement of the thermal insulation was about 20–45% due to internal moisture exposure increasing at the same time heat loss by an average of 38% (110 W), whereas thermal insulation decreased by 0–40% and heat loss increased by an of average 18% (46 W) due to external moisture depending on the outer fabric's permeability. Perspiration moisture from internal source evaporates through clothing due to absorption and desorption through permeable and semipermeable fabrics, and due to the pipe effect through garment openings also from impermeable clothing. Contrary to effects of the internal moisture, penetrated external moisture caused a long-term decrease in the thermal insulation of the all measured ensembles.

These findings are noteworthy in designing cold protective clothing for outdoor professions where work tasks cause occasional sweating e.g. in sparsely populated areas or in maritime conditions. The most critical situation was when clothing became wet from an external source e.g. water, snow or sleet, and the total thermal insulation remained decreased for a long period. In the subzero temperatures, the increased evaporative heat loss from the clothing will drop the skin temperatures, cause dramatic cooling of the body and increase the risk of accidents. Condensation of the moisture can be avoided or minimised by material choices and improving ventilation if high physical activity is performed in the cold. The cold and wet environmental conditions are expected to become more common in the future due to climate change, and protection should be considered accordingly for these requirements. In the future research and development, interactive solutions of moisture handling inside the clothing and smart adaptive insulation methods for dynamic physical activity levels should be focused on.

4.4 Heat Loss due to Wind

Research question 4 is answered by Papers II and IV: *How does wind and its direction affect dry heat transfer through layered clothing?* Direction of natural wind as well as body positions at work vary and their effect on clothing physiological properties of cold protective clothing should be recognised and used in material development. The articles analysed the effects of different wind speeds from different angles towards the thermal manikin in different body positions on cold protective ensembles made in different material combinations. In addition, unpublished results are presented in order to specify the findings of this chapter.

The results on wind effects on heat loss from the ensembles are combined from Papers II and IV into Figure 9. The ensembles had different air permeability, and they are categorized as permeable (PERM), semipermeable (SEMI) and impermeable (IMP), due to their fabric construction, used membranes, laminations or reflective layers.

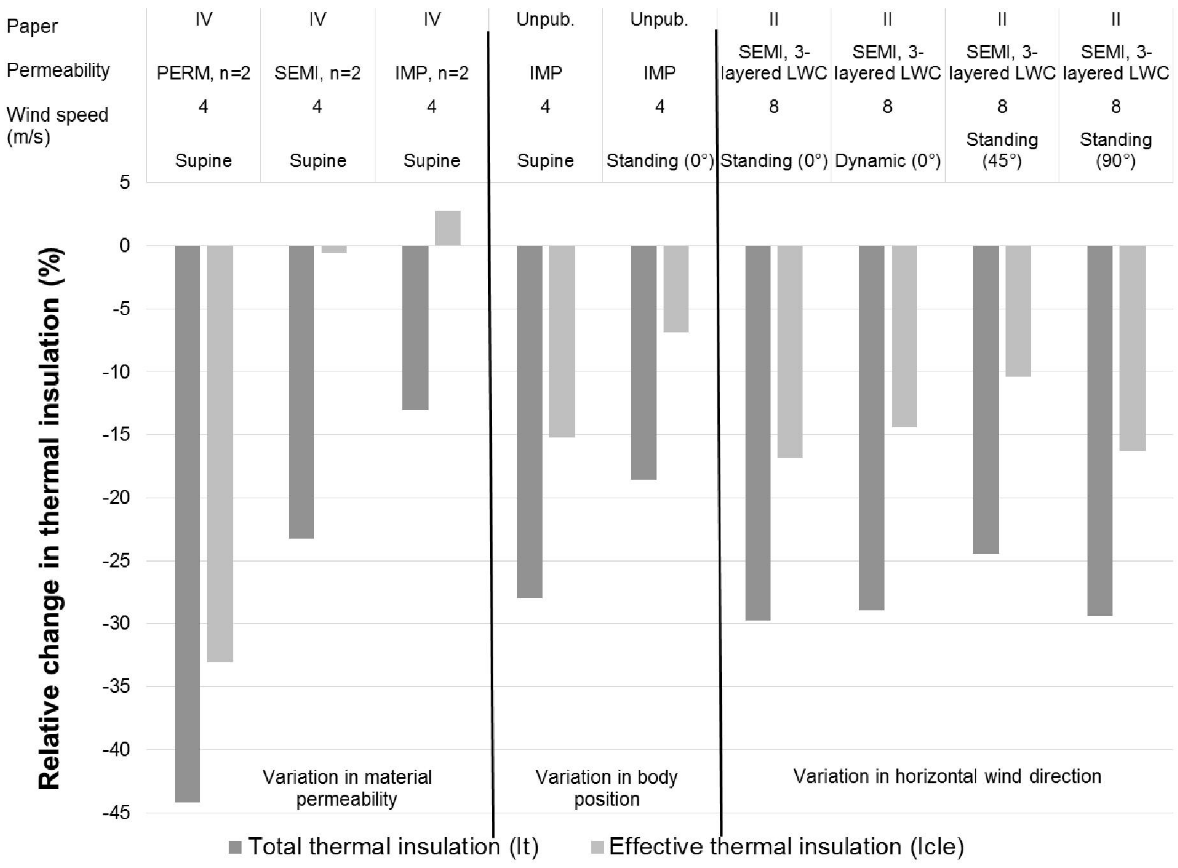

Figure 9. Influence of wind (4 and 8 m/s), body position and wind direction on total thermal insulation (I_t) and the effective thermal insulation values (I_{cle}) without boundary air layer.

In addition to the results from original publications, Figure 9 consists of effective thermal insulation values for all evaluated ensembles. The effective thermal insulation had on average about 14 percentage points (± 3.5, SD) lower change than total value. Breakdown of the insulating boundary air layer surrounding the clothing causes a higher decrease of the total thermal insulation. The moderate wind speed of 4 m/s decreased the I_a from 0.09 m^2K/W (0.58 clo) to 0.03 m^2K/W (0.19 clo) while standing, whereas measurement of the I_a in a high wind speed of 8 m/s could not be determined reliably, and on the basis of the literature the I_a was considered to be diminished (Anttonen et al., 1998a).

It is also seen in Figure 9, especially from effective values without boundary air layer, that wind speed of 4 m/s penetrates inside the permeable ensembles and increases convective heat loss causing a great decrease of thermal insulation, whereas semi permeable and impermeable layers in the ensembles prevented the effects of the wind, having only a minor decrease in the I_{cle}. The obtained results at supine position correspond well with the literature where is reported that a moderate wind speed (3 m/s) decreases the total thermal insulation in supine position of low insulation ensembles from 20 to 40%, and that of high insulation ensembles from 15 to 25% (Henriksson et al., 2009). Elsewhere it has been shown that high wind speeds (12 to 18 m/s) will decrease the thermal insulation of highly impermeable clothing ensembles from 30 to 40%. The decrease of the thermal insulation in wind is caused mostly because of boundary layer breakdown and compression effects (Havenith et al., 1990b; Holmér et al., 2001), and corresponds with the results of this study concerning change in the total thermal insulation values.

The results showed that the relative decrement due to the wind (8 m/s) in the standing and due to dynamic situations was about the same (Figure 9). The wind decreased the I_t (the I_{cle}) of the three-layered clothing by 30% (17%) as seen in the figure, and movement (walking speed of 0.51 m/s) of the thermal manikin in calm (0.3 m/s) on average by 16% (17%) as presented in Paper II, whereas the combined effects of wind (8 m/s) and walking movement decreased the I_t (the I_{cle}) of the three-layered clothing by about 29% (14%) being less than the sum of the individual effects. These results suggest that the effects of the wind by breaking down the surrounding boundary air layer, compressing air layers inside the clothing and probably to some extent conveying air layers from the clothing via ‘chimney effect’ are similar in both cases and the ‘pumping effect’ due to walking was diminished due to compressed air layers inside the clothing when wind speed increased. The literature supports the results of this thesis. It has been suggested that the combined effects of wind and walking decrease the thermal insulation by about 50% when decrement by wind was about 40% and by movement about 30% (Havenith et al., 1990b; Olesen and Nielsen, 1983). The results of this study suggest that the combined effect of the wind and movement on total thermal insulation was about 78% of the sum of the individual relative effects, whereas the combined effect from the literature was about 71% of the sum of the individual relative effects. Anttonen and Hiltunen (2003) have also proposed that the effect of walking is reduced in high wind speeds.

The local thermal insulation of the chest and back differed in a supine position both in calm and windy conditions having higher values on the chest side. Conductive cooling was stronger on the back due to the simulated cold ground (the steel plate) and compressed insulating covering fabrics due to body weight. Exceptionally the ensembles with the integrated mattress had higher thermal insulation on the back than on the chest. Interestingly, the effects of wind (4 m/s) were relatively similar on the chest and back sides. The effect of wind was about an average of 5 percentage points higher on the chest than back with permeable ensembles, whereas the semi- and impermeables ensembles had an average higher relative decrease in wind on the back than on the chest. However, only minor differences were found between the thermal insulation of the torso and legs in the studied ensembles in the supine position. Furthermore, when these results were compared with the results with the standing manikin, it was seen that the relative decrease due to the wind was smaller in the lower body parts than in the torso. This is most probably due to the higher contact surface area of the torso with the direct wind, causing a greater compressive effect on the torso than on the lower part of the body.

The decreased effect due to the wind on the thermal insulation differed the most between the permeability of clothing ensembles. The wind had the greatest effect when permeable ensembles were worn and the least when ensembles with wind-proof semi-permeable membranes or impermeable metallized fabrics were integrated into the ensembles. When the wind-proof ensembles were used, the wind transferred the heat simultaneously by three mechanisms: 1) breakdown of the boundary air layer around the clothing surface, 2) compressing air layers inside the clothing on the wind side of the body, and 3) increasing ventilation through formed air gaps on the other side of the body.

Wind and movement of the body increase ventilation inside the clothing, but at the same time moisture transportation is increased. Additional garment openings in impermeable cold protective clothing could be used to adjust ventilation and heat and moisture transfer inside the clothing, especially during high physical activity. In the literature (Anttonen et al., 1994), it has been reported that ventilation inside the clothing was increased by 125–200% when additional garment openings were used. Similarly, moisture transportation from the clothing was increased by 40−70% and moisture accumulations decreased. In addition, cold protective clothing design influences the ventilation inside clothing. Havenith et al. (1990a) have shown that ventilation is higher with overalls than with two-piece clothing.

Effect of wind direction and body position

The effect of the horizontal wind against the front side of the body on convective heat transfer is extensively studied (Anttonen, 1993; Havenith et al., 1990b; Havenith and Nilsson, 2004; Jussila and Anttonen, 2011a). In this thesis, the horizontal wind against the front side of the body is equivalent to the 0° wind direction in this measurement setup of the study. Other studied setups were 45° and 90° angles of the left side of the standing thermal manikin against the horizontal wind (Figure 9).

The results in Figure 9 show that the relative decrease due to wind (8 m/s) of the total thermal insulation was lowest when the thermal manikin was turned to a 45° angle to the wind direction being about 5 percent points smaller than at 0° and 90° angles against wind. When the thermal manikin was left side (90° angle) against the wind, the local thermal insulation was an average about 10% lower on the left side (the wind side) than in the right side, whereas the effective thermal insulation between left and right sides differed by less than 4% when the thermal manikin was at 0° and 45° angles against the wind.

When the body was facing the wind direction (0°), the contact surface area of the direct horizontal wind with the body and, thus, the compressed air layer underneath the outermost garments were the greatest. In addition, the 3D body scanning cross-sectional figures illustrated (Paper II) the higher compression of the outer layer when sideways (90°) against the wind than at a 45° angle. Earlier research (Anttonen and Hiltunen, 2003) pointed out that turning a thermal manikin to a different angle against horizontal wind changes the clothing thermal insulation, and the clothing took different shapes, especially on the chest and back. Contrary to the results of this study, they reported that the highest total thermal insulation was when the thermal manikin was sideways (90°) against the wind, and they did not find significant differences between angles of 45° and 90°. These different findings are caused due to different ensemble types, their material stiffness and thickness, which affect compression of the garment layers under direct wind. In this study, material did not compress when the wind direction was 45°, whereas compression was seen at 90° when the elliptical cross-profile of the thermal manikin assisted the compression under direct wind.

The heat transfer mechanism differed between the left and right sides of the body when the position of the thermal manikin was changed towards the horizontal wind direction. The 3D scanned cross-sectional figures revealed that the wind compressed the thickness of the air layers to the minimum on the wind side of the body, and thus the effective thermal insulation was decreased. On the other hand, the air layer thickness was increased on the opposite side and ventilation inside the clothing due to ‘chimney effect’ occurred. Earlier research (Anttonen and Hiltunen, 2003) reported that the clothing takes different shapes when wind speed exceed 4 m/s. The shape changes were reported to be the highest on the chest and back, whereas the changes were smaller with laminated fabrics. Turbulence of the wind is shown to decrease the thermal insulation by about 10% (Anttonen and Hiltunen, 2003). The turbulence of the wind is higher in natural environment than in laboratory conditions (about 3.3%) and the boundary air layer is broken more efficiently.

The measurements of the thermal insulation in Papers II and IV were made in two different positions, standing and supine, but the wind speed was different in these studies. On the basis of the earlier discussion in this thesis, it is known that the compressive effect of the wind on the effective thermal insulation is minor when the thermal manikin is in the supine position with legs toward the wind and effect of convection is higher than when standing because of the smaller direct contact surface and higher parallel surface to the wind. The wind (4 m/s) decreased the total thermal insulation in the supine position an average by 44, 23 and 13% with permeable, semi-permeable and impermeable ensembles, respectively. In the literature (Anttonen and Hiltunen, 2003; Havenith et al., 1990b; Jussila and Anttonen, 2011a) is reported that a wind speed of 4 m/s in a standing position decreased the total thermal insulation of measured clothing ensembles by 20–40% and by 15–40% in the supine position depending on the material thermal insulation and permeability (Henriksson et al., 2009).

To study difference between the standing and supine position in windy conditions, unpublished measurements were performed (Figure 9) with sleeping bag type of protective ensemble in a wind speeds of 0.3 and 4 m/s. The protective ensemble was wrapped with elastic string over the thermal manikin in both studied positions. These results showed that influence of wind was higher when being in the supine position than when standing. Convective heat loss and ventilation inside the ensemble due to wind were the dominant heat loss mechanisms in the supine position, because the wind blowing direction was parallel to the body. The elastic wrapping over the thermal manikin in the standing position diminished the compressive effect of wind as well as ventilation inside the whole body covering without typical garment holes, such as jacket hem, sleeve and leg ends. This may cause underestimated effect of wind in the standing position comparing to typical cold protective clothing systems.

Summary and future perspectives

In this chapter was studied how wind and its direction affected dry heat transfer through layered clothing. The moderate wind decreased the intrinsic thermal insulation without boundary air layer by 1−33% depending on air permeability of the ensembles. The clothing insulation declined in all cases despite the material or body position and, therefore, to prevent effects of the wind patterning of the garments and design of closures, tightenings and their placement should be carefully considered based on the results of the study. It was found that the combined effect of high wind speed and movement was about 80% of the sum of the individual relative effects. However, the effect of wind remained the same in the dynamic situation, whereas the effect of movement in wind was decreased. Therefore, protection against wind by material choices and designed elements are critical. Finally, it was found that body position and angle towards the direct wind direction changed the relationship between different heat transfer mechanisms and their effectiveness. The highest intrinsic thermal insulation was when the standing body was at a 45° angle to the wind direction when the compressive effect of wind was the smallest, whereas the moderate wind decreased the insulation due to convective heat loss more in the supine position than while standing. Locally, differences in heat loss due to wind were found between torso and legs in relation to direct surface area against the wind while standing. The local effects of wind should be applied in development of more effective ventilation systems in clothing for high physical activity in the cold.

In this study, the effects of wind from different directions towards the body were analysed from a wide perspective. The gained information should be applied in clothing design and development by taking into account the wind effects on different body segments and the air gaps formed in garments spotted by 3D body scanning. These results should be considered when designing more effective ventilation systems for removing excessive heat from cold protective clothing during heavy physical activity. In the future, advanced research in different body positions, such as sitting, should be performed to obtain accurate knowledge on the effects of high wind speeds, for example while driving a snowmobile.

4.5 Effects of Clothing on Human Responses

In this chapter, research question 5 is answered: *Are the found effects on properties of layered clothing significant for user's thermal comfort, coping and performance?* Paper III focused on thermal comfort and perceived performance during long-term cold exposure while wearing clothing systems from different decades from the 1940s until present time. Coping in cold was evaluated during prehospital maritime transportation in Paper IV with two different cold protective ensembles. The effects of cold on performance were studied in Paper V due to finger dexterity and usability features with different type of gloves. This chapter summarizes the effects of different types of clothing on human experience, thermal responses and performance in the cold climate, and thus shows the importance of well-designed protective clothing in meaning of correct material choices and functional details.

4.5.1 Thermal Comfort

Thermal comfort includes both sensations of heat or cold and skin wetness. The clothing physiological properties affecting a user's thermal comfort were assessed in Paper III by evaluating three different cold protective clothing systems from different decades (Traditional from 1940s, Model 1991 (M91), Model 2005 (M05)) during long-term (11 days) cold exposure. Subjective experiences in terms of thermal comfort were elucidated using two separate daily questionnaires: a clothing questionnaire and a surveillance card. Mean thermal and moisture sensations due to external source and perspiration with different type of clothing during the long-term cold exposure are presented in Figure 10.

The studied new clothing system M05 was compared with two reference clothing systems M91 and traditional coarse cloth clothing. These two systems were otherwise similar except that traditional coarse cloth outerwear made of a dense felted material was replaced with combat clothing in M91. The dense felted material has good air trapping properties providing good thermal insulation values but high levels of moisture absorbance and stiffness. The development in the new M05 system included improved adjustability of the clothing layers, and thus thermal insulation and wind protection as presented in detail in Paper III. In addition, the M05 had higher resistance to water penetration and lower weight. The same underwear was used with all the studied systems. All ensembles had a similar utilization rate.

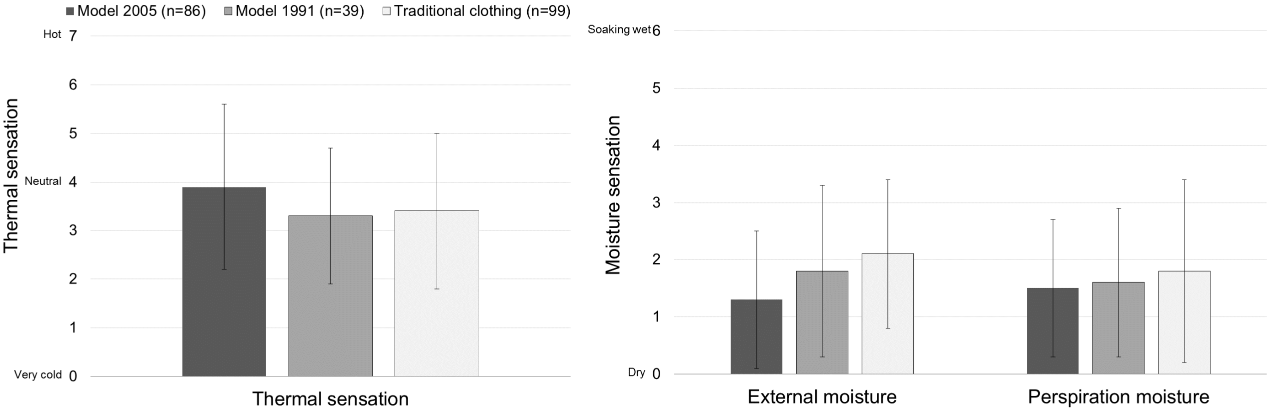

Figure 10. Mean (±SD) thermal sensations ($p<0.05$) and moisture sensations due to external moisture (ns) and perspiration ($p<0.05$) with three studied clothing ensembles: Model 2005, Model 1991 and Traditional clothing.

The clothing physiological results and perceived perceptions regarding the newly developed clothing (M05) were more positive than with the other clothing systems from earlier decades. The new system provided warmer thermal sensations (18%), dryer moisture sensations due to external moisture exposure (38%), and dryer moisture sensations caused by perspiration (17%) than the previous type of clothing system (M91). Protection against cold and wind was experienced as being significantly better with the newly developed (M05) clothing ($p<0.001$). The absorption properties of the mid layer clothing were improved by increasing the wool content. The wetting of the combat clothing layer was perceived alleviated by reducing the amount of hydrophilic cotton in the fabric. The materials and fibre contents of the snow and cold weather clothing layers remained the same, but their wetting was perceived reduced with more efficient repellent finishes. Wang et al. (2007) have studied that the fabric properties of four-layer clothing can significantly affect humidity and temperature distributions, and also thermal and moisture sensations during cold exposure of 90 minutes, whereas this study showed improved thermal and moisture sensations during long periods of cold exposure.

According to the study, the most challenging environment was not the cold as such but a combination of cold with perspiration during physical activity, external moisture and wet snow. The thermal sensations became significantly warmer with drier moisture sensations. The mean moisture sensations due to external dampness when wearing the M05 system corresponded to an "almost dry" sensation. The corresponding mean value for the other systems was “slightly moist”. A significant statistical correlation existed between the external moisture sensations and environmental temperature. The traditional clothing was affected most by external moisture, on account of the hydrophilic nature of its cloth, with a high wool content (WO 85%).

The mean moisture sensations due to perspiration were experienced as ‘almost dry’ with M05 and M91, and ‘slightly moist’ with the traditional system. Systematic differences between the clothing systems were seen, even though the difference were not statistically significant because all the test subjects were wearing the same type of inner layer. Therefore, the differences must have been caused by the absorption and wicking properties of the mid layer and the water vapour penetration properties of the outer layer. The mid layer clothing of the M05 and M91 systems differs in terms of both material and fit that of the M05 clothing fitting snugly and enabling quicker moisture transfer from the underwear.

Relating to the thermal comfort, the M05 system has improved adjustability of the thermal insulation even though the total thermal insulation is similar to that in other systems. Experiences of cold and wind were examined on a daily basis, and it was evident that the test subjects wearing the M05 clothing were not affected by the cold and windy conditions during training as much as the other test subjects. The differences in thermal comfort between the clothing systems were caused by the lower air permeability and higher resistance to water penetration of the M05 clothing, which also preserved its thermal insulation properties better under difficult ambient conditions and at times of physical labour than the older clothing systems.

Summary and future perspectives

Thermal comfort consists of thermal sensations and skin wetness (Fanger, 1970; ISO 7730, 1984). During long-term cold exposure, perceived perceptions of thermal and moisture sensations were clearly affected by different types of clothing systems from different decades. The newly developed system had the most positive perceived perception of the thermal sensations (18%), dryer moisture sensations in the presence of external dampness (38%), and dryer moisture sensations caused by perspiration (17%). These positive experiences were made possible by higher thermal insulation and resistance to water penetration, lower air permeability, optimum material choices and more feasible adjustability of the clothing layers.

This study pointed out that more feasible adjustability of clothing layers improved thermal comfort. However, in the future more fluent and proactive adjustment of the thermal insulation according to physical activity and ambient thermal conditions should be developed. This would maintain stable thermal comfort without excessive moisture accumulations in the clothing layers, thus avoiding after-cooling effect during low physical activity. The proactive adjustment system could consist of ventilation and a garment opening method that reacts on changes in skin and ambient temperatures. Earlier studies have shown that comfort sensations are highly dependent on inner layer materials (Ha et al., 1996 and 1998; Li et al., 1992; Stanton et al., 2014). Therefore, the material selection of the inner layer should be made on the basis of skin thermal and moisture sensations and material properties as discussed in Chapter 4.1.

4.5.2 Coping with Low Physical Activity

Coping of inactive persons in ambient conditions combining coldness, wind and moisture, with two different type of protective covers was examined in Paper IV. The inactive persons waited on the pier for boat transportation for twenty minutes. During half an hour of boat transportation in the uncovered part of the boat, the sitting inactive persons were exposed to wind speed of about 10–13 m/s due to driving speed. As presented earlier in Chapter 4.4, heat loss from the body to the ambient air increases when wind speed rises, and thus also the effective thermal insulation of the clothing decreased.

Layered winter clothing (LWC) with rain clothing (I_t = 0.53 m²K/W) was used as control clothing (CC). The protective cover (R3, I_t = 0.49 m²K/W) was selected on the basis of thermal insulation, protection against wind, moisture handling properties and functionality for transportation in authentic maritime conditions as presented in the original study. The R3 was used together with LWC and compared with the CC. In the study, four male subjects wore CC or LWC during the precooling period on the pier (20 min). The CC included the rain clothing, whereas additional covering was put on the layered clothing just before maritime boat transportation (30 min) began.

The relative humidity (Rh) between the inner and mid clothing layers was less than 50% and perceived moisture sensations did remain dry in both tested ensembles. The temperature and Rh between the clothing layers declined rapidly after transportation began and air movement increased highly due to driving when CC alone was used, whereas Rh remained relatively constant during the measurement when LWC was used with the covering (R3). This indicates that cold air due to highly increased air movement got under CC through sleeve cuffs, legs and the jacket hem, and thus conveyed warm air and moisture from the clothing, whereas the protective cover (R3) prevented air movement under the clothing through the jacket hem, cuffs and legs. Therefore, the temperature between the inner and mid layers inside the clothing with the protective cover was 1 °C warmer for about 25 minutes of the transportation than without it. However, at the end of the transportation, the temperature between the clothing layers was about the same in both ensembles (30.5 °C).

The mean skin temperature (T_{sk}) decreased by only 0.5 °C with the protective cover, which was about 31 °C during maritime transportation, whereas T_{sk} while wearing CC declined by 3 °C, making it about 29 °C at the end of the measurement. It has been determined that the discomfort limit for the T_{sk} of a healthy person is 31 °C and the tolerance limit is 25 °C (Lotens, 1988). General thermal sensation of the test subjects, before and after boat transportation, was 'slightly cool'. The core temperature (T_c) increased during the precooling period on the pier, but at the end of the transportation returned to the initial level with the protective cover, and to slightly below the initial level with CC. T_c remained on average between 37.1 and 37.4 °C in both tested ensembles, which is within 'comfort' limits according to Lotens (1988). Thomassen et al. (2011) have studied the warming effect of three different wrapping systems on humans. It was found significant differences between the systems in T_{sk}, metabolic heat production and thermal sensations, but not in rectal temperature.

Using the obtained knowledge from the study and comparing the results with the duration limited exposure (DLE) index based on standard EN ISO 11079 (2007), it was determined that protective covering with an insulation value higher than 0.46 m^2K/W provides sufficient protection for an immobile healthy person (58 W/m^2) during half an hour in −5 °C with high wind speed (10 m/s). This time was considered to be sufficient for prehospital maritime transportation in coastal areas. Use of a vapour barrier in the covering improves comfort and limits the shivering of an immobile person in the cold, windy and wet ambient conditions as well as if person has wet clothing (Henriksson et al., 2015).

The results of this thesis can be applied to the work environment by comparing required protection of the inactive person with break times of outdoor workers between work periods. The 'after cooling' effect can be significant during breaks after high physical activity, e.g. among forestry workers, especially if moisture due to sweating is not able to evaporate through clothing materials (Anttonen et al., 1993). Use of ventilation openings during heavy physical activity was shown to decrease moisture accumulations in the clothing layers.

Summary and future perspectives

Coping in low ambient temperatures requires protection of an inactive person against cold, high wind speeds and exposure to water splashes. According to the results a sufficient level of protection against ambient conditions and preventing heat loss from body, combines both insulating and water-resistant layers. Moisture inside clothing is important to evaporate through garment openings and fabrics to avoid strong after cooling effect during low activity periods especially after sweating during heavy work. However, the results indicate that in very low ambient temperatures to maintain thermal balance of the inactive person additional heating is required.

Cooling of the inactive person in the cold occurs firstly on extremities, such as fingers and toes, and unprotected skin areas, e.g. face, have a high risk of rapid cooling especially when exposed to wind. Sufficient protection of the whole body hinders cooling of the extremities, but protection of hands and feet should be more focused in the future, taking into account low activity periods during working day by additional thermal insulation or auxiliary heating.

4.5.3 Performance

Perceived physical and mental performance

Perceived physical and mental performance was examined in Paper III with test subjects using the three different cold protective clothing systems from different decades during long-term (11 days) cold exposure by two separate questionnaires. The subjects using the newly developed clothing (M05) rated their physical and mental performance significantly higher in the daily questionnaires than the others (Model 1991 (M91) and Traditional). The newly developed clothing kept users' thermal balance stable, resulting also in more stable level of daily perceived performance. Mean values of perceived physical and mental performance with three types of clothing from different decades are illustrated in Figure 11.

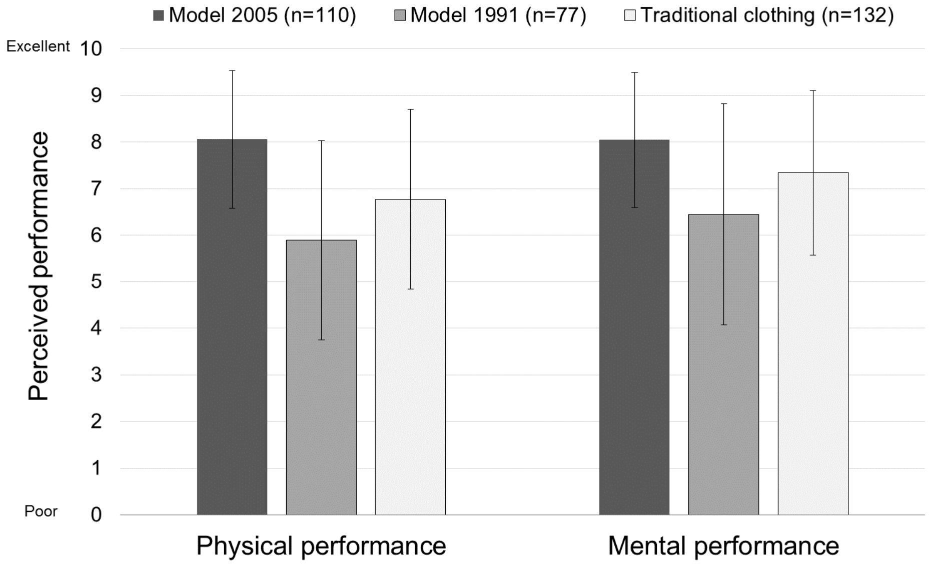

Figure 11. Mean (±SD) perceived physical ($p<0.001$) and mental ($p<0.001$) performance with three studied clothing ensembles: Model 2005, Model 1991 and Traditional clothing.

The effect of the clothing on physical performance was seen in the day-to-day variation, the differences being greater during the heavy physical training period. Thick, heavy, stiff clothing increases the physical load while performing tasks (Dorman and Havenith, 2009; Duggan, 1988). The total weight of the newly developed clothing (M05) was about 2 kg (10%) lower than the previous cold protective clothing M91. This reduction of the clothing weight decreases energy consumption by about 5.4%, according to Dorman and Havenith (2009). The greatest decrements in the weight were obtained in mid garments (30%) and the cold protective outer garments (7%). In addition, changes in the fit and flexibility of the mid layer were made to reduce limitation of movement of the arms and legs. Adjustment of the clothing thermal insulation was improved by using a long zipper from neck to hem of the mid shirt facilitating donning and doffing of the garment. These improvements were seen in higher perception of physical performance (37%) of the users wearing the newly developed clothing than the previous clothing (M91) during long-term cold exposure.

Significant differences ($p<0.001$) in users' perceptions of mental performance were found between the different clothing, and about 25% higher perceptions were reported with the newly developed clothing (M05). A significant correlation existed between the protective properties of the clothing (protection against cold and moisture) and mental and physical performance. The better water repellence of the M05 clothing kept it drier and meant that the decrease in thermal insulation was smaller than with the other clothing systems, and this may also have affected perceived mental performance. The perceptions were collected by two separate questionnaires: surveillance card and clothing questionnaire. Surveillance cards distributed and collected on a daily basis were used to allow the participants to evaluate their experiences. The results were used in combination with those from the clothing questionnaires to assess the significance of the clothing used.

Manual dexterity

Working outdoors, many tasks require manual labour and sufficient finger dexterity when using e.g. equipment and tools or performing maintenance tasks. Fingers and hands are the first to cool in the cold, and already a few degrees decrement in the finger skin temperatures will impair sensitive perceptions and muscle power. Further cooling will decrease hand and finger performance (Enander, 1984) and the number of errors increases (Geng, 2001). Also protective gloves hinder the movement, dexterity and sensitivity of the fingers and hand, and thus manual performance (Bellingar and Slocum, 1993). Glove size, material thickness and flexibility impair the manual performance by 11–31% (Kinnunen et al., 2002). In Paper V was demonstrated the effects of low temperature on material properties, and thus manual dexterity by usability and finger dexterity tests while using different type of gloves and bare-handed. The mean level of finger performance was tested according to the finger dexterity tests with different glove types in both warm (+27 °C) and cold (−20 °C) temperatures.

The cold decreased finger dexterity levels by about 17% compared to warm conditions in the scale from 1 to 5, where level 5 provides the greatest finger dexterity. The highest level of finger dexterity was maintained with the firefighters' leather glove both in cold and warm conditions; even the relative decrease (20%) was slightly higher than with other gloves (about 15%). The overall thickness of the leather gloves (including leather and lining) was thinner than that of the other gloves. The thickness of the glove has a strong negative correlation with finger dexterity (Havenith and Vrijkotte, 1993). The glove consisting of both leather and textile decreased the level of performance most at both temperatures. The test gloves were somewhat already used, and we assumed that a dirty glove stiffens more in the cold than a clean glove.

The lowest temperature in which it is possible to maintain practical bare-handed performance for more than a few minutes is −18 °C (Rogers and Noddin, 1984). Therefore, a person should be able to use hand-held tools or manual devices, e.g. communication equipment, in very low temperatures while wearing protective gloves. The usability tests of the TETRA phones in the cold showed that, in general, the usability of the push-buttons of the phones differed significantly depending on whether they were used with different gloves or bare-handed. For each feature, the usability of the phones was evaluated as best when the firefighters' leather gloves were used compared to situations when the other gloves were worn. The poorest usability values resulted from the use of the leather/textile glove. These findings are in relation to the results obtained by finger dexterity tests.

Influence of the low ambient temperature on material properties, and thus manual dexterity and usability features, differed with different type of materials. Manual dexterity was maintained the highest when the thinnest material made from leather was selected. In the future, material stiffness and friction properties in the cold should be studied in detail. Especially synthetic materials may become hard and may crack in very low temperatures. In addition, many protective working gloves with good gripping properties are produced from synthetic materials, which start to stiffen below zero temperatures (Kinnunen et al., 2002). The gripping properties of the glove are important especially in the cold because the muscle power is decreased due to cooling.

Summary and future perspectives

The results show how development of the clothing system as a whole will lead to not only improved clothing physiological improvements, but the effects will be seen in perceived performance. Statistically significant differences in perceived physical (37%) and mental (25%) performance were found depending on type of protective clothing and garment material. A greater experience of users’ physical performance was obtained by lower total weight of the clothing and improved flexibility and adjustability of the mid layer, whereas perceived mental performance was supported by improved protection against cold and moisture. It was demonstrated that material cooling affects finger dexterity by 17% due to changes in material properties, such as stiffness, and thus hindered movement of the fingers. Gloves made of leather sustained the highest level of finger dexterity in the cold.

Future development is still needed to find lighter and, at the same time, insulating fibre materials and fabric constructions to improve performance in outdoor work in the cold climate. Friction between fabric layers increases the energy consumption and limits the movement of the arms and legs. Moreover, it should be noted that moisture increases the material friction and moisture accumulations should be avoided. Special attention is needed for protection of the hands while performing manual tasks. Auxiliary warming systems reacting on skin cooling could be considered for smart solutions for future hand protection in very low ambient temperatures and in wind.

4.6 Assessment of the Research

This chapter evaluates the used methodology in the thesis. The study evaluated cold protective clothing, its protective properties in different work and environmental conditions and its effects on users' responses from a holistic point of view. Therefore, methodology was selected to utilize a wide range of testing facilities from fabric measurements to clothing systems on a thermal manikin, and further on humans in an authentic work environment.

Evaluation and measurement of human experiences and comfort perception at work have been of great interest during recent years. Recently, development of the portable measurement technology using wireless sensors and dataloggers for studying real exposures and human experiences as well as properties of the protective clothing while working have been concentrated on. Research focus nowadays has turned from thermal and clothing physiological aspects to holistic and multidisciplinary point of views as part of the risk management to support safe and healthy work and improve at the same time productivity.

In this thesis, clothing physiological properties of the textile materials were measured in controlled laboratory conditions by the sweating hot-plate (Paper I). The method provided the most suitable, comparable and exact way to analyse different inner fabrics as part of three-layered material combination for sweating situations in cold climate. Accuracy of the measured thermal resistance by using the sweating hot-plate has been reported to be less than 5% (Anttonen, 1993). The factors affecting the variation were changes in turbulence of air flow on the material surface. The difference in thermal insulation between the lowest and the highest value was about 8%. The found differences between the inner layer materials were small, but impact in practical use may be considerable, especially in 'after cooling' effect caused by heavy physical activity in the cold.

The thermal manikin was used to evaluate clothing physiological properties of the clothing ensembles (Papers II and IV). The measurements performed in controlled laboratory conditions in the climatic chamber took into account effects of air inside the fabric and between clothing layers, pattern fit and ambient conditions to thermal properties of the clothing. All the measurement setups were based on international and European standards and produced in an accredited laboratory of the Finnish Institute of Occupational Health. Measurement equipment is calibrated regularly according to relevant standardization (EN 342, 2004; EN ISO 15831, 2004). According to interlaboratory round robin tests between eight European laboratories, the reproducibility of the thermal insulations tests in a single laboratory was reported to be less than 3% (Anttonen et al., 2004). Repeatability of the measurements is mostly affected by donning and doffing the clothing between tests by variation in positioning of air gaps and fabrics inside the clothing (Kuklane et al., 2004; Kuklane and Dejke, 2010).

The standardized methodology to determine thermal properties of the clothing was also applied with 3D scanning methodology (Paper II). The used software for 3D body scanning provided accurate body girth measures and cross-sectional figures of the different clothing layers. Comparison of them with the calculated air layer thicknesses provided reliable knowledge of air gaps and layer thicknesses between garment layers. The software was not originally designed to measure the air gaps and content under garments and, thus, the measures had to partly be performed manually or partly omitted. However, the method provided objective results to evaluate distribution of air gaps inside the clothing and to find the problematic areas of conductive heat loss or ventilation. The simultaneous use of the method with the thermal manikin limited the ambient temperature to be at the lowest +10 °C. In the manikin test procedure in the standard EN ISO 15831 (2004) it is identified that the T_a is set to at least 12 °C below the thermal manikin's T_{sk} to provide reliable results. Whereas in this study the T_a was about 24 °C lower than T_{sk}. On this basis, the measured results can be stated as reliable. To obtain minimum error, less than 5%, due to ambient air temperature, it should be in the range of −15–15 °C (Anttonen et al., 2004). The thermal insulation increases when ambient temperature declines, because the thermal transmission occurs in most part through the air and the thermal conductivity of air changes 0.3%/°C (Fourt and Hollies, 1970). This change in the thermal conductivity would mean that the measured values in this study would be about 3% higher at ambient temperature of −10 °C than in the current condition. However, the measured values were compared between each other, and therefore used ambient temperature was accepted.

The effects of the protective clothing on human experiences were evaluated by test subjects in the laboratory (Paper V) and in authentic field conditions (Papers III and IV). The measurements provided information on users' perspective based on subjective questionnaire evaluation (Paper III) as well as objective thermophysiological (Paper IV), manual dexterity and usability tests (Paper V). The number of test subjects for both thermophysiological and usability tests was limited to four males due to economical, practical and training limitations. However, subjects tested all protective ensembles, which increases the number of performed tests. Contrary to the laboratory conditions in authentic field conditions, ambient conditions, test subject activity control, donning and doffing of the garments and follow-up cannot be managed, and they may vary between measurements. According to previous study (Anttonen, 1993), thermal insulation of fabric and thermal manikin measurements differ by about 30%. Whereas static test subject measurements corresponded well with the results of the thermal manikin. Moving of the thermal manikin is shown to decrease the insulation by about 10−20% (Anttonen and Hiltunen, 2003), whereas movement of the subject decreased the insulation by about 25% (Anttonen, 1993).

Two separate questionnaires, the clothing questionnaire and the surveillance card, were conducted during field measurements (Paper III). Reliability and reproducibility of the questionnaires were ensured by using standardised and tested questions (EN ISO 10551, 2001; Wang et al., 2007).

The surveillance cards were distributed by the military personnel throughout the training, whereas the clothing questionnaire was administrated by the researchers. This may have had an influence on different answer ranges between the questionnaires. However, the number of answers was sufficient for statistical analysis. The studies were performed separately to diminish the effect of the psychological effect of the new clothing on users' experiences. The surveillance card contained questions referring to daily state of health, mental and physical performance, mood, motivation, stress level, nutrition and cold experiences, and they were combined later on with the clothing questionnaire. Users themselves could not be asked to compare the clothing systems, because the clothing was not rotated between the users due to practical and hygienic issues associated with the long period of military manoeuvres in the forest.

In this thesis, cold protective clothing development for military purposes from early clothing systems from the 1940s until the present time was evaluated. The differences between the measured clothing physiological parameters were not considerably substantial in all cases, but still significant differences in human experiences and responses were found. Interestingly, development along the history was not always positive, and some material choices impaired thermal and moisture handling properties of the clothing produced in the 1990s, but finally the recent development has resulted in improved protection.

The studied and compared cold protective solutions were based on traditional textile technological solutions available or already in use for the moment. Development of the smart and interactive materials (Seeberg et al., 2013) and integrated auxiliary heating systems (Jussila et al., 2013; Wang et al., 2010; Wang and Lee, 2010) have been done for a couple of decades, but especially within protective clothing solutions these solutions are not yet applied into practice mostly due to challenges in quality control and standardization, and economical factors and challenges with durability and maintenance. However, these solutions are expected to be applied in protective clothing and equipment in the future, especially in extreme conditions.

The thesis managed to produce novel information on clothing physiological properties of the cold protective clothing and their effects on users' experiences and responses in real time activities, and effects of the long-term clothing development process. The gained multidisciplinary knowledge promotes the international cold related science from the protective clothing point of view and suggests new solutions and directions for future research and development as well as standardization of protective clothing and their test procedures (EN 13402-3, 2004; EN 342, 2004; EN ISO 15831, 2004). The study resulted in solutions for cold protection of soldiers, rescuers and tourism workers, and protection in challenging emergency situations in cold maritime conditions was also studied. These occupations and cases are relevant especially in the Arctic area, where industrial activity, such as petroleum and gas and fishing industries, is expected to grow significantly in coming years and where the obtained results are applicable. The results are noteworthy for development of occupational safety and health management, and it should be considered as a competitive advantage for companies in northern areas.

5 Conclusions

Industrial and logistical activities in the Arctic are expected to increase significantly in the coming years. In this thesis it was shown that the most challenging work environment consists of ambient conditions, such as low temperatures, strong wind speeds, and moisture especially in maritime areas. The study produced scientific results from a multidisciplinary perspective on constructing layered cold protective clothing, and its clothing physiological properties in varying physical activities and ambient conditions. It was clearly shown that development of the cold protective clothing during several decades improved thermal comfort, coping and performance during long-term cold exposure. The findings are significant for improving occupational safety, health, and well-being as well as productivity in outdoor processes. This chapter summaries the answers to the presented research question based on the results and discussion of this thesis.

5.1 Main Scientific Conclusions

The inner layer forms the base for thermal and tactile comfort sensations. The study found that the inner layer has the most influence on moisture handling properties, such as heat content for evaporation, drying time, decrease in thermal insulation when wet, and heat loss through layered fabric combination varied by approximately 40 W between ensembles. Suitable properties were provided by inner fabrics made of inherent hydrophilic wool or hydrophobic polyamide.

The still air content inside the cold protective clothing corresponds with an intrinsic insulation of one clothing layer and tight clothing provided close to 20% lower thermal insulation than loose-fitting. The study showed that the optimum outermost clothing size maintaining the highest thermal insulation and preventing the heat loss the most in wind while moving was one size larger than suggested in the European standardisation (EN 13402-3) and recommendations for clothing size in wind while moving. The 3D scanning method applied for measuring the air content between layered clothing enabled systematic and objective research analysis.

Moisture transfer mechanisms and their effects on the clothing insulation in low ambient temperatures differed whether the moisture appeared from internal or external sources of the clothing. Moisture from internal sources was able to evaporate through clothing due to absorption and desorption through permeable and semipermeable fabrics, and from impermeable clothing due to pipe effect through garment openings. Whereas absorbed external moisture into the outer fabrics caused 15–30% lower immediate decrease in thermal insulation of the all ensembles despite the material permeability properties than when moisture occurred internally, the decrement stayed stable until the end of the measurements. Subzero ambient temperature prevented the cycle of moisture evaporation and condensation inside the wet clothing and enabled ice formation onto the fabric surface.

The wind speed of 4–8 m/s decreased the intrinsic insulation up to 33% depending on material air permeability, body position and wind direction. The effect of simultaneous body movement and exposure to high wind speed lowered the ‘pumping effect’ inside the clothing, but kept the influence of the wind the same as the individual relative effect. Body position and wind direction towards the body created different heat transfer mechanisms on the different parts of the body by compressing air layers inside the clothing, creating ‘pipe effect’ and convection.

Finally, in this study it was reported that the development of clothing properties during several decades resulted in improved human responses, such as thermal comfort, coping and performance in the cold. Higher resistance to water penetration and thermal insulation, lower air permeability, optimum material choices (wicking, moisture transfer, stiffness in the cold), low weight and more feasible adjustability of the clothing layers provided the users’ warmer thermal (18%) and drier moisture (27%) sensations and, thus, improved thermal comfort and perceived physical (37%) and mental (25%) performance. In the thesis was demonstrated that very low ambient temperature affected material properties, such as stiffness, and thus finger dexterity was lowered by 17% due to hindered movement of the fingers. Gloves made of leather sustained the highest level of finger performance in the cold.

In the cold, the risk of fatal cooling of an injured person is increased. Coping of inactive person in the cold, high wind speed and moist ambient conditions was enabled by protective clothing combining insulating and water-resistant layers. It provided sufficient temperatures on the skin and inside the clothing as well as low relative humidity underneath the clothing during maritime emergency evacuation.

5.2 Recommendations

Recommendations for the future research, development and design of cold protective clothing are addressed based on the most significant findings of this thesis:

- To prevent intensive ‘after cooling’ effect during breaks in the cold and provide thermal comfort at work, the inner layer material should be selected based on moisture transfer properties. The most suitable properties were provided by fine woollen micro fibre fabric that support warm thermal sensation also under moist conditions. The fabric thickness should be low in case of high physical activity to enable short drying time.
- Dry and still air should be considered as one raw material of the cold protective clothing system to obtain the highest thermal insulation while moving in windy ambient conditions. Therefore, one size greater girth measures should be applied in standardization for clothing size (EN 13402-3), designing and patterning cold protective clothing as well as in training and education of users.
- Correct clothing size of the layered cold protective clothing should be taken into account in the standard for cold protective clothing (EN 342) and in the determined testing procedures (EN ISO 15831) to enable comparable results, as the equation for corrected thermal insulation in wind while walking does not take into account the effect of clothing size.
- At subzero temperatures, permeability of the outer fabrics should be considered based on the source of the moisture, whether it is appearing from an internal or external source. Permeable and semipermeable fabrics are able to evaporate moisture through the fabrics, whereas in impermeable materials ventilation openings should be considered.
- To improve adjustment during changing physical activity and protection against the wind, the optimum ventilation system should be created by material choices, designed elements of adjustable closures and openings and their placement taking into account wind direction, body positions and local effects of the wind on different body parts when using the clothing.

Future research should take into consideration an effect of the protective clothing itself on productivity as well as economical aspects in industrial processes to encourage companies to improve occupational safety in cold work. Well-being at work is supported also by comfort, which is emphasized by thermal and sensorial sensations in the cold climate. Natural materials, such as wool and leather, were shown to have beneficial moisture handling and thermal properties for cold climate, but development of their finishing treatments should be continued for having proper maintenance properties without losing their natural features. Future research and development of cold protective clothing should focus on interactive and smart solutions of moisture handling, ventilation, auxiliary heating and thermal insulation of the clothing for dynamic physical activities in varying ambient conditions and working positions. In addition, smart solutions should be studied for hands and feet protection while working manual tasks with low physical activity. These future aspects were found to be essential to enable safe and healthy work in the Arctic areas.

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Original Papers

Paper I

Kirsi Jussila, Hannu Anttonen, Raija Ketola

Functional Underwear for Military Use in Cold Climate

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Functional underwear for military use in cold climate

M.Sc. (Eng.) Kirsi Jussila [1], Prof. Hannu Anttonen [1] and B.Sc. (Eng.) Raija Ketola [2]

[1] Finnish Institute of Occupational Health,
Aapistie 1, FI-90220 Oulu, Finland
[2] The Finnish Defence Forces, Western Finland Logistics Regiment / Quartermaster Depot
Harvialantie 2, FI-13210 Hämeenlinna, Finland

kirsi.jussila@ttl.fi

ABSTRACT

Underwear is the functional part of the military clothing system and it is affected by middle and outer clothing layers. Main function of the underwear is to maintain conscript's skin dry and improve thermal and moisture sensations on the skin. Underwear is exposed to both water vapour and liquid exchange. Thus, material for underwear garments has to be evaluated regard to moisture handling and hygienic function. Moisture properties are affected by fibre material and construction, fabric's porosity construction and overall thickness of the clothing system. On moisture transfer and accumulations in the underwear can be affected by military combat clothing's adjustability of convection and ventilation. Underwear gives also additional protection against heat radiation. This study aims to support and to improve performance in military tasks and survivability in cold climate. In addition, the objective was to find the optimum materials for conscript's underwear in cold conditions. Properties of eight different materials for conscript's winter underwear were tested in laboratory conditions. We tested material and clothing properties such as thermal insulation, water retention properties, drying time, colour change by simulated sweat, influence of wash on properties and dimensional change of fabrics. Also in laboratory conditions have been tested wetting and drying properties with test subjects. During the Finnish Defence Forces' infantry and artillery winter field training was observed underwear's moisture handling properties and its affect on survivability. Moisture accumulations and drying time of wet underwear vary between underwear materials and fabric construction. The construction of the underwear fabric is prefer to be non-plain for avoid wet textile's sticking on the skin. Outer clothing layers have a great impact on underwear's functionality and soldiers' survival and military performance in cold climate. Long term use of clothing impaired underwear's wetting and drying properties.

1.0 INTRODUCTION

Underwear is the functional part of the military clothing system and it is affected by middle and outer clothing layers. Main function of the underwear is to maintain conscript's skin dry and improve thermal and moisture sensations on the skin. Underwear is exposed to both water vapour and liquid exchange. Thus, material for underwear garments has to be evaluated regard to moisture handling and hygienic function. Suitable winter underwear material would have good tactile properties, high wicking properties, being light weight and non-compressible. [1, 2] According to previous research when wearing one layer of thermal underwear in winter the same level of thermal comfort can be maintained as those at around 5°C higher temperature [3]. The contact layer near the skin has important role in whole clothing system [4].

Evaporative moisture from a human is 30g/h at rest and high physical activity increase it to 4kg/h. Moisture properties are affected by fibre material and construction, fabric's porosity construction (knit or weave fabric) and overall thickness of the clothing system. Different fabric constructions have differences in capillary absorbencies, air content between fibres and yarns and also in wicking properties. In addition moisture transfer properties and moisture accumulations in the underwear can be affected by military combat clothing's adjustability of convection and ventilation. [1, 4]

Functional underwear in cold does not increase friction between the combat clothing layers. Differences of up to 50% have been found between the friction values of dry fabrics. Clothing with low friction between the layers increases performance by 7-13% relative to clothing with high friction according to previous studies. [5]

Military combat clothing system has to protect against fire and sparks. Materials against skin have to be non-fusible or fire retardant. Underwear gives also additional protection against heat radiation. [4]

According to previous study washing of fabrics increases the insulation of woollen material to a certain extent. Each use and washing reduces the amount of material in the fabric and in long run the thermal insulation reduces. [6]

This study aims to support and to improve performance in military tasks and survivability in cold climate by finding optimum materials for conscripts' underwear in cold environmental conditions. In addition, the objective was to find the optimum materials for conscript’s underwear in cold conditions.

2.0 MATERIAL AND METHODS

2.1 Tested winter underwear materials and clothing combinations

Properties of eight different materials suitable for winter underwear for military conscripts were tested in textile laboratory. The underwear fabrics were measured together with the new Model 2005 (M05) middle clothing fabric (Terry knit: WO 70%, PA 30%) and combat clothing fabric (weft satin weave: CO 50%, PES 50%). In Table 1 is given information about tested underwear fabrics.

Table 1. Descriptions of tested winter underwear fabrics.

Underwear	Material
Winter 1	PES 50%, CO 33%, MAC 17%, rib knit
Winter 2	PP 40%, CMD 30%, CO 30%, plush
Winter 3	WO 46%, PP 42%, PAN 12%, plush
Winter 4	PA 95%, EL 5%, plain knitted
Winter 5	PES 100%, plush
Winter 6	PES 100%, interlock
Winter 7	PES 77%, WO 23%, 2-layer
Winter 8	WO 100%

In this research have been used also combat clothing systems from previous decades, Model 1991, M91, and course cloth. The underwear belonging to the M91 consisting 50% of polyester, 33% of cotton and 17% of modacrylic, the middle layer clothing was 80% of wool and combat clothing was 65% cotton and 50% polyester. The other reference clothing system used in addition to M91 was the coarse cloth system. These two systems were otherwise similar except that the M91 combat clothing was replaced with coarse cloth outerwear made out of a dense felted material consisting 85% of wool and 15% polyamide. This material had good air trapping properties and thickness, giving it good thermal insulation values but high levels of moisture absorbance and stiffness.

2.2 Laboratory measurements

We tested material and clothing properties such as water retention properties, thermal insulation, drying time, colour change by simulated sweat, influence of wash on properties and dimensional change of fabrics. Also in laboratory conditions have been tested wetting and drying properties with test subjects.

The underwear materials were tested when they were new and after ten washes. Water vapour permeability, drying properties and thermal insulations of eight different materials suitable for winter underwear were measured using the artificial skin model. The tests are quoted for an ambient temperature of -15°C and air movement was 1.0m/s. The measurements were made according to SFS 5681:1991 standard. Over the artificial skin was placed Gore-tex membrane. Water condensed into different clothing layers was measured by weighting fabric before and after the tests.

The dynamic sweating simulation test was performed feeding water 300g/m²h during 1.5 hours. This is corresponding with hard physical work. After the water feed, measuring continued during two hours. After the measurement drying energy can be calculated. Needed drying energy is calculated using 1 below:

$$E = \frac{1}{60} * (\sum_{0}^{120} (P(t) - P(120)) \qquad (1),$$

where E is needed drying energy (Wh), P(t) is needed heating power of the artificial skin when time is t (measuring period is one minute) and P(120) is heating power of the artificial skin at end of the test (120 min). Then, time when 90% of the moisture has dried from the initial moisture can be calculated.

Dimensional changes of the winter underwear fabrics were tested according to EN 340:2003, ISO 5077:1984 and ISO 6330:2000 standards.

Colour fastness to perspiration was tested according to EN ISO 105-E04:1994 standard. The underwear materials were handled with alkaline and acid solutions. Colour changes of the fabrics after the tests are evaluated based on grey scale. Grade 5 is given when original and tested has no notable difference.

In laboratory conditions were tested with test subjects wetting and drying properties and an effect of utilization on these properties. The test was performed an ambient temperature of 22°C on a foam mattress where was absorbed water of 3l/m³. Test subject was laid on his elbows on the mattress during 20 minutes (Figure 1). The test was made for examine moisture retention properties of new and used clothing layers. The test subject was wearing rubber boots (Model 1991). The clothes were weighted before the test and three times after the test, once in hour.

Figure 1. The test subject lying on the water absorbed mattress during the moisture retention tests.

2.3 Questionnaires in military manoeuvre

The effects of middle and outermost clothing layers on functionality of the underwear and test subjects' moisture sensations in long-term cold exposure were tested with conscripts during the Finnish Defence Forces' winter field training for infantry and artillery (Otso -05 manoeuvres in December 2005). The Middle and outermost clothing layers were three combat clothing systems from different decades, the new Model 2005 (M05) combat clothing, the previous Model 1991 (M91) system and coarse cloth system. The same underwear, M91, was used with all the systems, and they all had a similar utilization rate. The test subjects were healthy volunteers from among the male conscripts taking part in the manoeuvres, average age 20 years, and the clothing systems were distributed at random. Subjective experiences in terms of survivability and physical and mental performance were elucidated using daily questionnaires. The data were analysed separately for the three clothing systems to enable comparison.

The clothing questionnaires were used in this research to monitor moisture sensations. The detailed instructions about what to wear during military manoeuvres were prepared in co-operation with clothing experts from the Western Finland Logistics Regiment of the Finnish Defence Forces. The ballistic protection and armoury of all the test subjects conformed to regulations.

The clothing questionnaires were distributed 11 times during the military manoeuvres and a total of 242 completed forms were obtained. Of the conscripts that answered daily, twelve were wearing the coarse cloth system, ten the M05 clothing and seven the M91 clothing. Some changes were made to the garments used daily during the manoeuvre. The winter combat clothing had been worn on 41 occasions altogether and the ballistic vest on a total of 48 times. These answers included 23 given by conscripts using the M05 clothing and 25 using the M91 clothing.

The data were analysed statistically using the Statistical Package for the Social Sciences (SPSS). This enabled direct analysis of question and cross-tabulation of the data. The test subjects were given code numbers in the database, so that their identities were not revealed at any stage in the research.

3.0 RESULTS AND DISCUSSION

3.1 Material properties

The tested underwear fabrics are not thick with relation to whole combat clothing system. Consequently, the change in thickness is not significant after the ten washes; change is between 0 to 13% in all materials. Washes and used of the fabrics cause pilling and furthermore increase of the fabric thickness. Underwear thicknesses are presented in Table 2 when they are new and after ten washes. Effect of ten washes on underwear material fabrics' dimensional chances is shown in Table 3. The dimensional change is greater in warp direction than in weft.

Table 2. Thicknesses of new and ten times washed underwear materials and the percentage difference in thickness after washing.

Underwear	Thickness (mm) new	Thickness (mm) 10 times washed	Difference (%)
Winter 1	1,3	1,3	0
Winter 2	1,0	1,1	+10
Winter 3	1,2	1,3	+8
Winter 4	1,3	1,3	0
Winter 5	1,2	1,3	+8
Winter 6	0,8	0,9	+13
Winter 7	1,0	1,1	+10
Winter 8	1,0	1,0	0

Table 3. Effect of washes on dimensional changes of the underwear materials.

Underwear	Dimensional changes after 10 times washes (%)	
	warp	weft
Winter 1	-11	4
Winter 2	-11	1
Winter 3	-7	-8
Winter 4	-6	-2
Winter 5	-3	-3
Winter 6	-3	-4
Winter 7	-8	-4
Winter 8	-5	-4

Moisture accumulations increase along the number of washes. This is consequence of thickening of material and loss of the finishing chemicals over the fabric structure. Moisture accumulations of the new and ten times washed in the different clothing layers after perspiration simulation test are presented in Figure 2.

Desorption times of the underwear fabrics were shorten after ten washes except with polyamide and woollen fabrics. Determined desorption time needed for 90% dried from initial moisture of the new and ten times washed underwear fabric is given in Table 4.

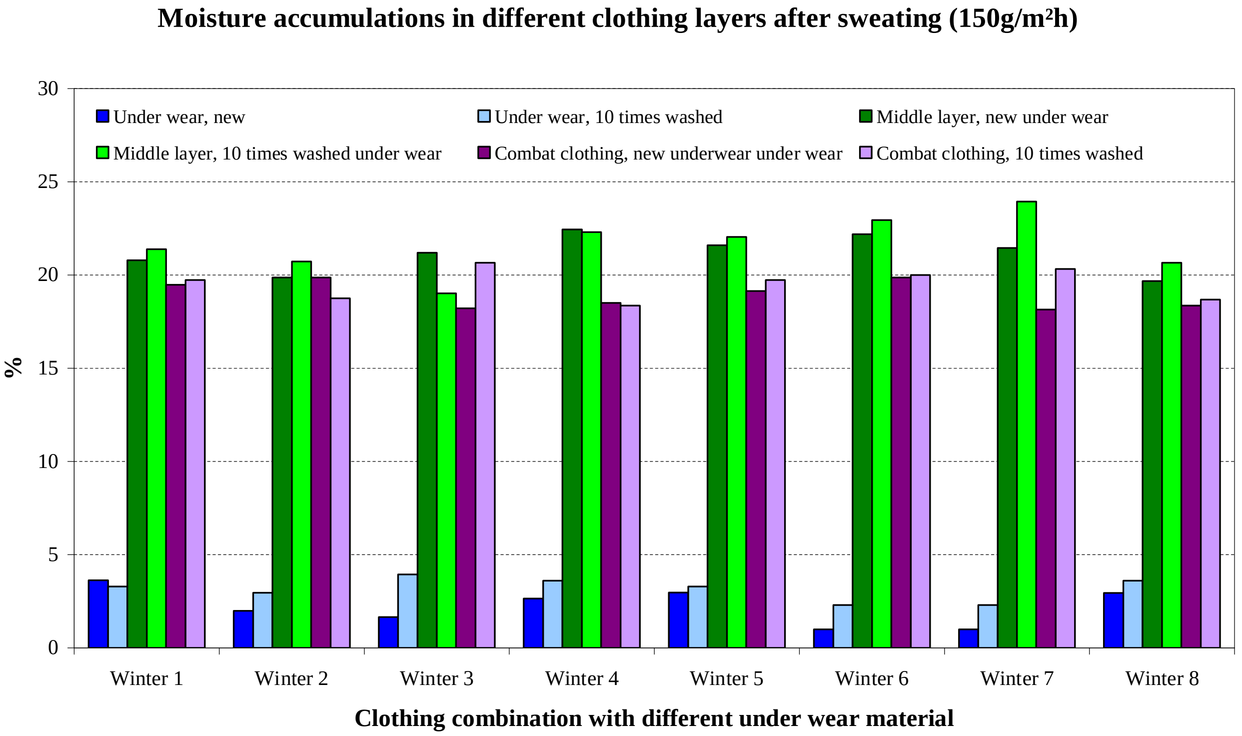

Figure 2. Moisture accumulations using the new and ten times washed underwear fabrics in different clothing layers, T_a=-15°C, sweating rate 150g/m²h.

Table 4. Time needed for desorption of winter underwear fabrics, Ta=-15°C, sweating rate 300g/m²h.

Material combination	Time when 90% dried from initial moisture (min)	Time when 90% dried from initial moisture (min) 10 times washed	Difference (%)
Winter 1	28	24	-14
Winter 2	44	24	-45
Winter 3	33	21	-36
Winter 4	19	26	+37
Winter 5	27	20	-26
Winter 6	45	24	-47
Winter 7	39	17	-56
Winter 8	22	30	+36

The clothing combinations were measured with the new M05 middle clothing and combat clothing fabrics. Underwear materials do not has high thermal insulation values. Consequently, the effect ten washes are not significant. Generally, reduce of the thermal insulation caused by moisture absorption is smaller with 10 times washed underwear fabrics, because materials were also thickened during the washes. Measured dry and wet thermal insulation of the new and ten times washed underwear fabrics are presented in Figure 3.

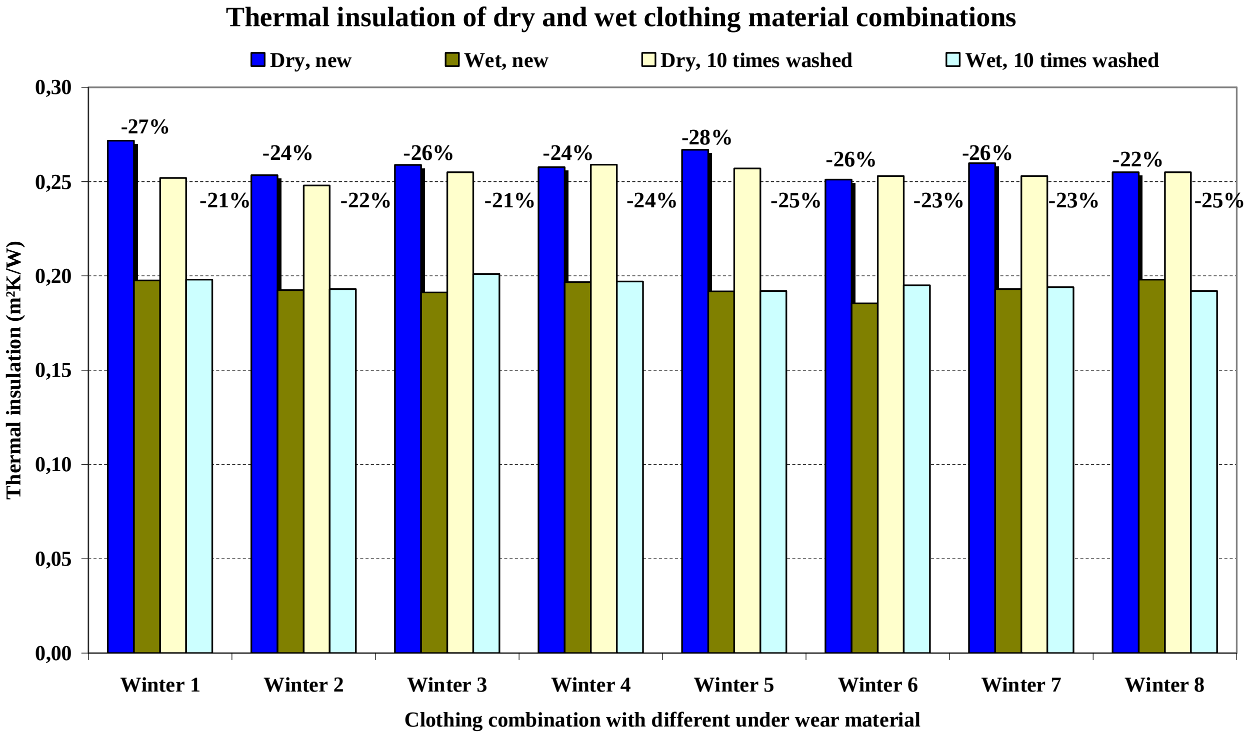

Figure 3. Thermal insulation of the new and ten times washed underwear materials, T_a=-15°C, sweating rate 150g/m²h

Colour fastness to perspiration of the different tested winter underwear fabrics are presented in Table 5. All tested materials had excellent resistance to perspiration.

Table 5. Colour fastness to perspiration of the underwear materials.

Underwear	Color	Change of color Alkaline solution	 Acid solution
Winter 1	Green	5	5
Winter 2	Black	5	5
Winter 3	Black	5	5
Winter 4	Black	5	5
Winter 5	Dark green	5	5
Winter 6	Green	5	5
Winter 7	Grey / Black	5	5
Winter 8	Black	4/5	4/5

3.2 Effect of other clothing layers on functionality of the underwear

The Figure 4 illustrates the effect of the different middle and outermost (M05, M91 and course cloth system) clothing layers on perspiration moisture sensations when the underwear is the same with all combat clothing systems. The moisture sensations caused by sweating of the test subjects were dryer when they were using the newly developed M05 combat clothing system than when using systems from earlier decades (M91 and course cloth) even the underwear was always the same.

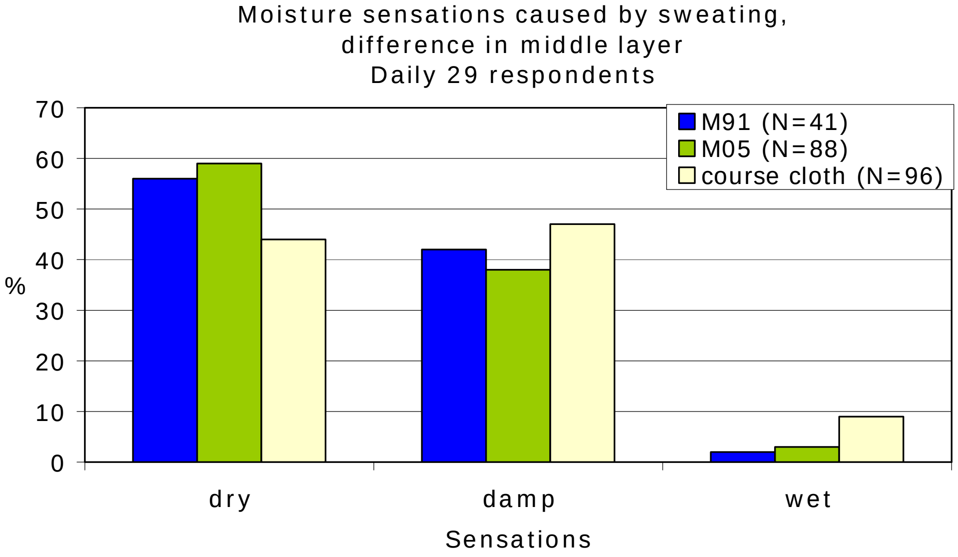

Figure 4. Sweat moisture sensations wearing three different military combat clothing during military manoeuvre and effect of middle and outer clothing on underwear.

3.3 Effect of long-term use on functionality of the underwear

In Figure 5 is illustrated water penetration into underwear material with new and used clothing layers, used under and middle clothing with new outermost layer and with new under and middle clothing with used outermost layer. The effect of utilization rate is significant when the outermost layer is used.

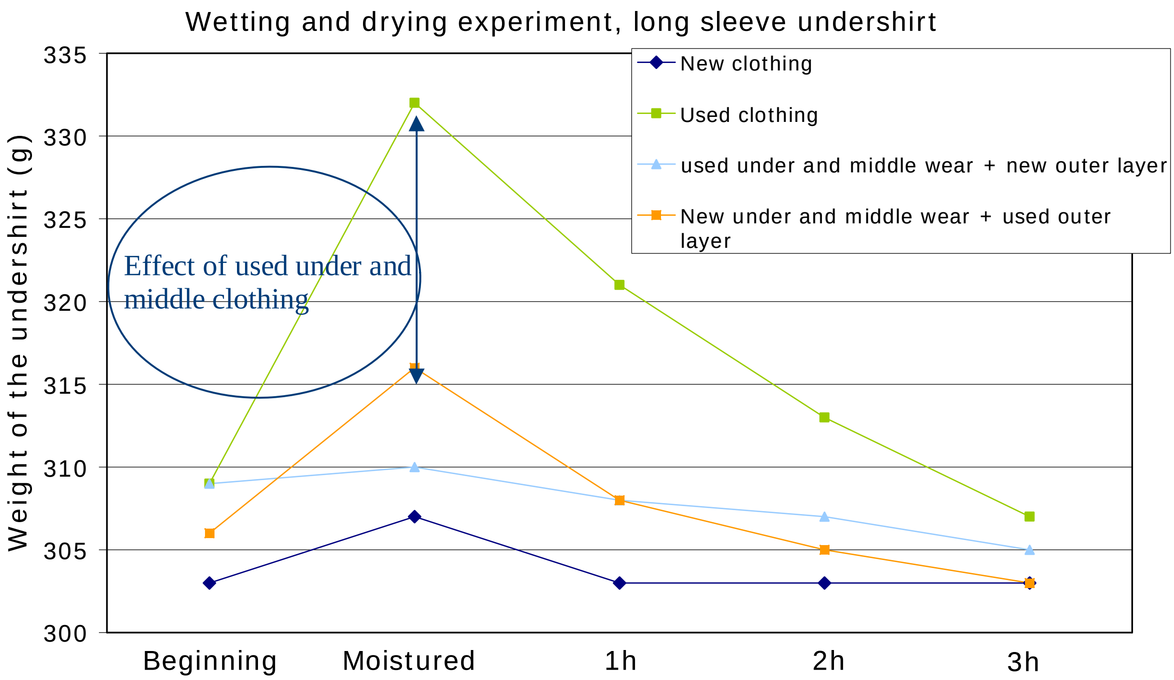

Figure 5. Influence of use of underwear and middle clothing on wetting and drying properties, Ta=+22°C, water content on the ground 3l/m²

4.0 CONCLUSIONS

Properties of eight different underwear materials for conscripts were tested in laboratory conditions. We tested material and clothing properties such as thermal insulation, water retention properties, drying time, colour change by simulated sweat, influence of wash on properties and dimensional change of fabrics. Also in laboratory conditions have been tested wetting and drying properties with test subjects. During the Finnish Defence Forces' infantry and artillery winter field training was observed underwear's moisture handling properties.

Moisture accumulations and drying time of wet underwear vary between underwear materials and fabric construction. The construction of the underwear fabric is prefer to be non-plain for avoid wet textile's sticking on the skin. In cold environmental conditions underwear's ability to transfer moisture to next clothing layer in short time period supports conscripts' physiological properties after moderate or high activity performance. Thermal insulation of the underwear did not affect notably on combat clothing's total thermal insulation. This research suggested that polyester/wool underwear material did meet overall the best results.

Outer clothing layers have a great impact on underwear's functionality and conscripts' survivability and military performance in cold climate. Non-fusible properties of underwear can be improved by textiles with one part of natural fibres, such as wool. Long term use of clothing impaired underwear's wetting and drying properties.

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Paper II

Kirsi Jussila, Marjukka Kekäläinen, Leena Simonen, Helena Mäkinen

Determining the Optimum Size Combination of Three-Layered Cold Protective Clothing in Varying Wind Conditions and Walking Speeds: Thermal Manikin and 3D Body Scanner Study

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Research Article

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Determining the Optimum Size Combination of Three-Layered Cold Protective Clothing in Varying Wind Conditions and Walking Speeds: Thermal Manikin and 3D Body Scanner Study

Kirsi Jussila[1*], **Marjukka Kekäläinen**[2], **Leena Simonen**[2], **Helena Mäkinen**[1]

[1]*Finnish Institute of Occupational Health, Aapistie 1, FI-90220 Oulu, Finland*

[2]*Centria University of Applied Sciences, Talonpojankatu 2, FI-67100 Kokkola, Finland*

[*]**Corresponding author:** Kirsi Jussila, Finnish Institute of Occupational Health, Aapistie 1, FI-90220 Oulu, Finland, Tel: +358 30 474 6089; E-mail: kirsi.jussila@ttl.fi

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Abstract

Garment fit and still air between clothing layers affect heat transfer through the clothing and thus the thermal insulation. Wind and body movement decreases clothing insulation by causing ventilation inside the clothing and by compressing air layers. The objective was to find the optimum size combination of three-layered clothing at two different wind speeds, and in stationary and walking situations, and to evaluate the effect of the wind direction on thermal insulation and air gaps inside the clothing. The clothing ensembles consisted of three layers (base, mid, outermost layer) in twelve different size combinations. The thermal insulation of the ensembles were measured in a climatic chamber (ambient temperature 10 °C, wind speed 0.3 m/s and 8 m/s) using both a static and moving thermal manikin. Whole body and cross-sectional figures of each clothing layer were taken by a 3D body scanner. The results showed that in calm conditions, static total thermal insulation was higher when the mid- and outermost layers were larger in size. When air movement was added by wind and body movement, thermal insulation reached its highest value when the outermost layer was one size larger than recommended in EN 13402-3.

Keywords: Cold protective clothing; Clothing size; Thermal manikin; 3D body scanning; Cold; Wind

Introduction

In cold conditions, the thermal insulation of clothing must be adequate for sustaining body heat balance. If both ambient temperature and physical activity are low, the required thermal insulation is so high that a multi-layered clothing system is needed. It is well known that garment fit and still air between clothing layers and in textiles affect heat transfer through the clothing and thus also affect thermal insulation [1-4]. In a previous study using one clothing layer on the torso, the thermal insulation value increased with a thicker air layer entrapped between the clothing and skin, but the value started to drop if being higher than the optimum air layer thickness [1]. Another study determined the maximum thermal insulation value of two-layered clothing on the torso in relation to air volume between the garment layers [3].

In real conditions, air between clothing layers does not form uniform layers, but air gaps are formed. Air gaps inside clothing are not evenly distributed over the body and the number of small air gaps is greater than of large ones [5]. It has been found that in tight-fitting clothing, air gap thickness was almost constant for all body parts, whereas in loose-fitting clothing the air gap thickness was typically about 40% larger, and the largest differences were distributed around the sections of abdomen, lower back, lumbus and anterior and posterior pelvis [6].

Several environmental and user-related factors are known to influence the thermal insulation of cold protective clothing. Wind increases convective heat loss and compresses air content inside the clothing, which decreases thermal insulation [2,7-9]. It is also known that body movement causes a ‘pumping effect’, which increases air movement and ventilation inside the clothing, and thus heat transfer from the clothing increases and clothing insulation is reduced [2,8,10,11]. As regards the interaction effects of body movements and wind on thermal insulation, it has been reported that the higher the wind speed, the smaller the effect of movement, such as walking [8,12]. In addition, the ‘pumping effect’ was found to be greater when clothing permeability was lower [8]. When evaluating the insulation properties of clothing, the effects of wind speed and human movement can be taken into account by correcting for static insulation values [8,10]. Clarification is needed of these effects on the clothing thermal insulation of different clothing sizes. Based on the scientific literature, it is still not properly known how wind direction towards the body affects the thermal insulation of cold protective clothing.

Air content in clothing can be measured by pinching the fabric from different points of the body or by calculating the difference between the clothing measures and manikin or test subject [1,13]. Recently, 3D body scanning methodology has been used to analyse garment fit and air gaps inside clothing. This method has also been used in several studies to evaluate air layers in flame protective clothing and their relation to thermal insulation and burn injuries [5,14,15]. The 3D scanning method has proven to give comparable results with manual measurements and is a valuable tool for objective ratings and the fit evaluation of garments [3,5,6,16-19].

The aim of this study was to find the optimum size combination of three-layered, cold protective clothing through measurements using a thermal manikin and 3D body scanner in a climate chamber. The purpose was to deepen the knowledge on the effects of air content and clothing size in cold and windy conditions. In addition, we aimed to clarify the influence of wind direction against the body, and its influence on effective thermal insulation and air gap distribution inside the clothing.

Material and Methods

Thermal manikin and clothing ensembles

An aluminum thermal manikin (Finnish Institute of Occupational Health, Helsinki, Finland) consisting of twenty segments was used in the measurements. It has the size of male person with a height of 176 cm, chest circumference of 96 cm, waist 88 cm, hip 96.5 cm, thigh 55 cm, calf 37 cm, and 1.89 m^2 body surface area. According to the body measures, the body type of the thermal manikin was 'normal' (C), the height group was 176 ± 3 cm, and the clothing size was M or between sizes 48 and 50, based on girth measures of the chest and waist [20,21].

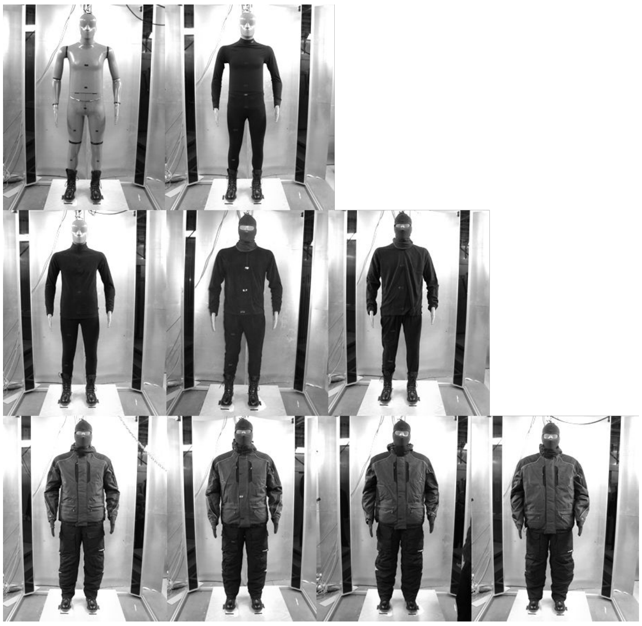

Figure 1: The three measured clothing layers in different sizes and nude thermal manikin from upper left: nude thermal manikin and base layer (size S); middle left: mid-layer sizes XS, M, L; lower left: outermost layer sizes 48, 50, 52, 56. The measurement points were marked by tape (chest, waist, hip, thigh, calf) to indicate the cross-sectional evaluation points in 3D body scanning.

	Base	Mid layer	Outermost layer
Material	Single knit: 66% PES, 29% CV, 5% EL	Microfleece: 100% PES	Fabric: 500D Invista Cordura®, Sinisalo® membrane Filling and lining: 100% synthetic fibre
Thickness	0.7 mm	1.5 mm	4.8 mm
Air permeability			1.0 mm/s
CV = Viscose, EL = elastane, PES = polyester			

Table 1: Material information of the three clothing layers (base, mid- and outermost).

The measured clothing ensembles included three layers (base, mid- and outermost). The outermost layer was two-piece clothing in four sizes (48, 50, 52, 56), the mid-layer was in three sizes (XS, M, XL), and the base layer was size S in all cases (Figure 1).

The strap at the hem line of the outermost jacket was slightly tightened. Table 1 provides information on the clothing layer materials and table 2 shows the measured combinations of the different layer sizes. The thickness of the garments was measured in accordance with the EN ISO 5084 standard [22].

Clothing	Base	Mid-layer	Outermost layer
C1	S	XS	48
C2	S	XS	50
C3	S	XS	52
C4	S	XS	56
C5	S	M	48
C6	S	M	50
C7	S	M	52
C8	S	M	56
C9	S	XL	48
C10	S	XL	50
C11	S	XL	52
C12	S	XL	56

Table 2: Sizes of different layers of measured clothing ensembles.

Thermal insulation measurements

The thermal insulation of the dry cold protective clothing ensembles was measured in a climate chamber (length 10.3×width 4.4×height 3.3 m) of the Finnish Institute of Occupational Health. The thermal insulation was measured according to standards EN ISO 15831 [23] and EN 342 [24], using both static and moving (walking speed 0.51 m/s, 45 double steps/min) thermal manikin. The moving thermal manikin simulates walking by moving both arms and legs during the experiment. The thermal insulation values were evaluated on whole body and locally in the separate segments of the thermal manikin. The surface temperature of the thermal manikin was set to 34.0 ± 0.1 °C [23]. Calibration of the used equipment was performed according to the standards.

The ambient temperature in the climatic chamber was adjusted to 10 °C, in accordance with the used standards [23, 24]. The relative humidity in the climatic chamber was not controlled during the experiments and was measured as about 40 ± 5% on average. The EN ISO 15831 standard [23] requires the ambient temperature to be set at least 12 °C below the thermal manikin's mean surface temperature to provide reliable results. In addition, the simultaneously used 3D body scanning equipment was sensitive to subzero temperatures. Two different wind speeds were selected to simulate low, 0.3 m/s, and high, 8.0 m/s, wind conditions. The low wind conditions were represented by intrinsic air flow in the climatic chamber and simulated calm wind conditions. The effect of the wind direction on thermal insulation, at high wind conditions (8 m/s) was measured by turning the thermal manikin to three different angles towards the wind, 0°, 45° and 90° (Figure 2). The wind (8 m/s) blowing horizontally from the front of the thermal manikin corresponded with the 0° angle, and when the thermal manikin was turned 45° and 90° to the wind, the left side of the thermal manikin was facing the wind. For practical reasons only one ensemble (C3) was chosen to determine the effect of wind direction.

Figure 2: Effects of wind direction (wind speed 8 m/s) on effective thermal insulation (I_{cle}) of clothing ensemble C3, tested at angles of 0°, 45° and 90° to the wind.

The clothing insulation was evenly distributed over the body, thus the total thermal insulation (I_t) and the resultant total thermal insulation values consisting all garments, enclosed air layers, and boundary air layers were calculated using serial model by equations 1 and 2 [23]. The thermal insulation values are presented in SI units (m^2K/W).

$$I_t \text{ and } I_{tr} = \Sigma_i f_i \left[\frac{(T_{si} - T_a) \times a_i}{H_{ci}}\right] \qquad (1)$$

$$\text{and} \quad f_i = a_i / A' \qquad (2)$$

where I_t is the total thermal insulation of the clothing (m^2K/W), f_i is the surface area factor of each manikin zone, T_{si} is the average manikin temperature (°C), T_a is the air temperature (°C), a_i is the surface area of the manikin zone (m^2), H_{ci} is the wattage of the manikin zone (W), and A is the total surface area of the manikin (m^2).

The effective thermal insulation (I_{cle}) and the resultant effective thermal insulation (I_{cler}) from skin to outer clothing surface of the ensembles were determined by equations 3 and 4:

$$I_{cle} = I_t - I_a \qquad (3)$$

$$\text{and} \quad I_{cler} = I_{tr} - I_{ar} \qquad (4)$$

where I_a is the insulation provided by the air layer around the nude static thermal manikin (m^2K/W), and I_{ar} is the insulation provided by the air layer around the nude moving thermal manikin (m^2K/W).

Evaluation of garment size by 3D body scanning

The undressed static thermal manikin and each clothing layer in different sizes were scanned on the static thermal manikin by a 3D body scanner using Human Solutions ScanWorX: Anthroscan software. A total of 31 scanned whole body pictures were taken. Each separate 3D-scanned clothing layer and undressed thermal manikin was overlaid into one picture using the x,y,z coordinates of the software. This ensured the correct location of each scanned layer.

The same dressing protocol was followed before each experiment to make sure the changes in air gaps were minimized. In all of the whole body pictures, the thermal manikin wore socks and boots. The hip of the thermal manikin was locked to give it a stable standing position.

From the scanned figures, cross-sectional measurements were made at five points: the chest (distance from the ground 133 cm), the waist (113 cm), the hip (94 cm), the thigh (72 cm), and the calf (39 cm). The used software was able to estimate the areas missed during scanning, for example, under the arm and the crotch. However, these missed areas were considered as outliers. The measurement points were marked by tape to indicate the cross-sectional points on the thermal manikin and the different clothing layer surfaces (Figure 1).

Air content determination

To evaluate the air layer thickness inside the clothing system, the body girth of each clothing layer and the thermal manikin were measured by a 3D scanning system at five different points, as described in the previous section. The thickness of the air layer (AG) between the clothing layers was calculated using equation 5 [1]:

$$AG = \frac{Lg - Lm}{7.14} - \frac{THm}{2}, \qquad (5)$$

where AG is the thickness of the air layer (cm), L_g is the body girth of the upper garment (cm), L_m is the body girth of the manikin (cm), TH_m is the compressed thickness of fabric (cm), and constant 7.14 is the mean value of 2π and 8, as the real cross-section of the body girth is between a circular and rectangular shape.

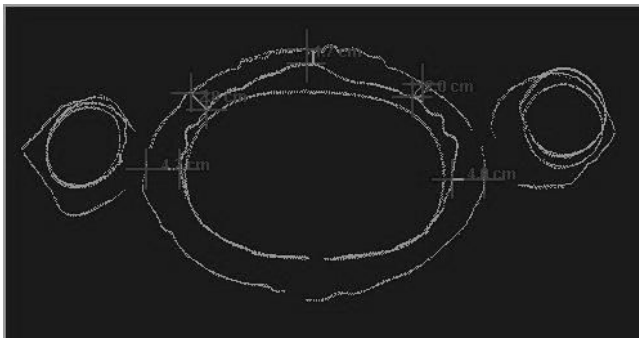

Figure 3: Thickness of air layers between clothing layers estimated from cross sections of 3D-scanned pictures from the waist.

The cross-sectional pictures of each clothing combination (C1 – C12) were pooled into one picture illustrating the layered clothing system. The thickness of the air layers between the clothing layers were also estimated at ten sites from these pooled pictures by using the Anthroscan software (Figure 3). Total average values were also calculated at the front and back and both sides.

Results

Thermal insulation of different sized clothing ensembles

Static thermal insulation

In calm conditions (0.3 m/s) with the stationary thermal manikin, the effective thermal insulation (I_{cle}) without the boundary air layer was used to analyse relative changes in the insulation values of the different clothing size combinations. The insulation of the surface air layer (I_a) of the nude stationary thermal manikin on clothing area in calm conditions (0.3 m/s) amounted to 0.090 mK/W (0.58 clo). The I_{cle} varied from 0.42 to 0.54 m^2K/W (2.7 – 3.5 clo) as shown in figure 4.

The relative difference in measured values ((I_{cle_min} – I_{cle_max})/ I_{cle_max} × 100 (%)) was about 23%. The I_{cle} was higher when the mid-and outermost garments were larger in size. In windy conditions (8 m/s) the boundary air layer around the ensembles broke down due to air movement. In wind the static thermal insulation of the ensembles increased when the outermost garments were larger in size, but the effect of different mid-layer sizes was not significant. The relative decrease in the static clothing thermal insulation caused by wind ($(I_{cle\_calm} - I_{t\_wind})/ I_{t\_wind} \times 100$ (%)) was on average about 15% (standard deviation (SD) ± 2.3). The relative decrease by wind was higher when the outermost clothing size was larger.

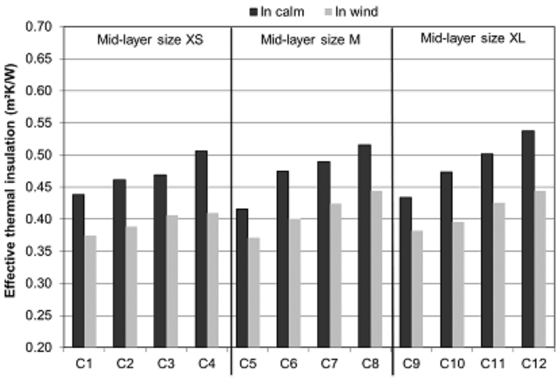

Figure 4: Effective thermal insulation (I_{cle}) of clothing ensembles in calm (0.3 m/s) and wind (8 m/s) with static thermal manikin. In each 'mid-layer size' section, 1st ensemble consists the smallest outermost clothing and 4th the largest.

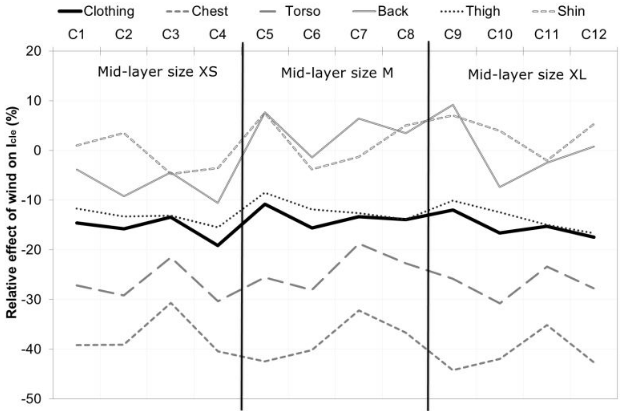

Figure 5: Relative effect (%) of wind (8 m/s) on effective thermal insulation (I_{cle}) on different body parts and whole clothing area. In each 'mid-layer size' section, 1st ensemble consists the smallest outermost clothing and 4th the largest.

Closer evaluation of the local I_{cle} values on the torso in calm (0.3 m/s) revealed that the I_{cle_torso} increased when the outermost garment was larger in size, and the size of the mid-layer garment did not have a remarkable influence. The I_{cle_torso} varied from 0.34 to 0.50 m^{2}K/W (2.5 – 3.2 clo) in calm conditions. In windy conditions, the highest static thermal insulation value on the torso was measured when the mid-layer garment size was M and the outermost garment sizes were 52 and 56. The Icle on the legs (thigh and shin) was the greatest when the outermost garment was the largest in both calm and windy conditions. The I_{cle_legs} varied from 0.47 to 0.57 m^{2}K/W (3.0 – 3.6 clo) in calm conditions. Figure 5 presents the relative effect of the wind on the static thermal insulation on part of upper and lower body and whole clothing area. The relative decrease by wind on I_{cle} on the torso as well as the chest was the smallest, 21% (± 2.3) and 33% (± 2.3) respectively, when the outermost garment was a size 52. On the legs (thigh and shin), the relative decrease by the wind on I_{cle} was the smallest, on average about 4% (± 2.3), when the outermost clothing size was the smallest.

Resultant thermal insulation

The resultant effective thermal insulation (I_{cler}) was used to analyse relative changes in the insulation values of the different clothing size combinations in calm conditions (0.3 m/s) with the moving thermal manikin (walking speed 0.51 m/s). The insulation of the surface air layer (I_{ar}) of the nude moving thermal manikin on clothing area in calm conditions (0.3 m/s) amounted to 0.084 m^{2}K/W (0.54 clo). The I_{cler} of the ensembles in calm varied from 0.37 to 0.42 m^{2}K/W (2.4 – 2.7 clo). The relative difference in measured values ($(I_{cler\_min} – I_{cler\_max})/ I_{cler\_max} \times 100$ (%)) was about 12%. In wind (8 m/s) the boundary air layer around the ensembles was lost. The clothing thermal insulation measured by the moving thermal manikin in both calm and windy conditions did not reveal significant differences between different mid-layer sizes. When the outermost clothing layer was larger, the clothing thermal insulation tended to be greater. A relative decrease in the resultant clothing thermal insulation caused by wind ($(I_{cler\_calm} - I_{tr\_wind})/ I_{tr\_wind} \times 100$ (%)) was on average about 10% (SD ± 3.5). The relative decrease of clothing thermal insulation by movement in calm conditions was on average about 17% (SD ± 3.9) and about 13% (SD ± 3.4) in the wind. The combined decrease of the clothing thermal insulation caused by walking and wind (8 m/s) was on average about 26% (SD ± 4.9). The relative decrease by wind, movement or their combination was higher when the outermost clothing size was larger.

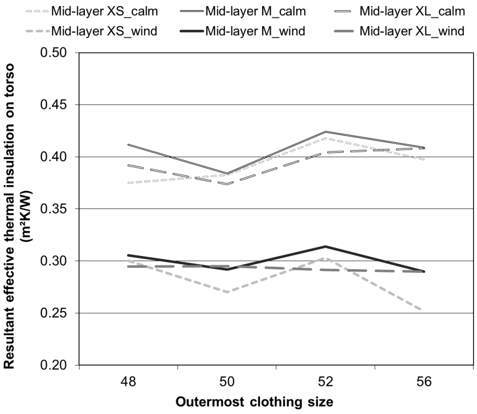

Figure 6: Resultant effective thermal insulation (I_{cler}) on torso measured in calm (0.3 m/s) and windy (8 m/s) conditions with moving thermal manikin.

Examination of the local I_{cler} on the torso showed that the values were at their highest when the mid-layer size is M and the outermost layer was 52 in both calm and windy conditions (Figure 6).

The combined effect of wind (8 m/s) and movement decreased I_{cler} on the upper and lower body relatively the greatest when the outermost garments were the largest in size and correspondingly the least when outer garments are the smallest (Figure 7).

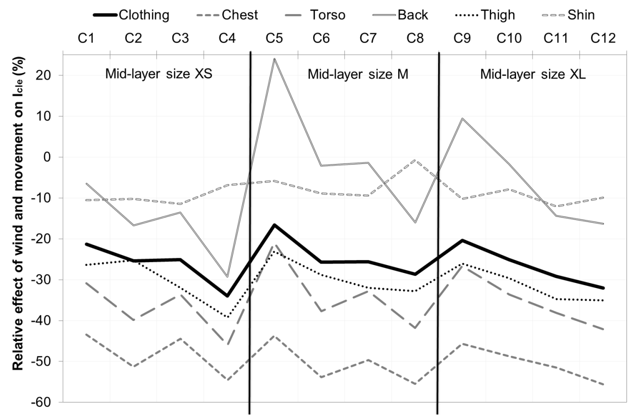

Figure 7: Relative effect (%) of wind (8 m/s) and movement (walking) on effective thermal insulation (I_{cle}) on different body parts and whole clothing area. In each 'mid-layer size' section, 1st ensemble consists the smallest outermost clothing and 4th the largest.

Air content in layered clothing

The girth of each clothing layer and the difference between the garments and the body at five body points were determined from the cross-sectional pictures, and the differences in the girths are presented in table 3.

	Base layer	Mid-layer	Outermost layer
XS/48	-	7.2 cm	26.3 cm
S/50	0.3 cm	-	29.2 cm
M/52	-	17.8 cm	34.9 cm
XL/56	-	28.4 cm	45.8 cm

Table 3: Difference in girth at the waist compared to girth of unclothed thermal manikin.

The thickness of the air layer (AG) between the outermost garment and the unclothed body was calculated (Formula 5) and measured from the cross-sectional figures. The measured results were about 14% higher than the calculated results (Figure 8).

Relation between thermal insulation and air content

The thermal insulation in windy and walking situations was highest when the mid-layer was size M. The relation between the thermal insulation on the torso and air layer thickness from the skin surface to the outermost layer at the waist is presented in figure 9.

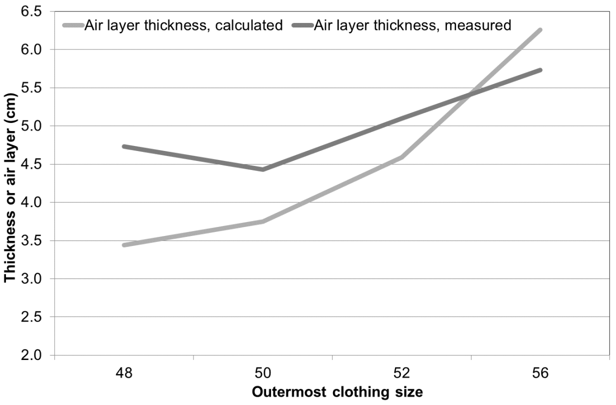

Figure 8: Thickness of air layer between outermost garment and unclothed thermal manikin at the waist.

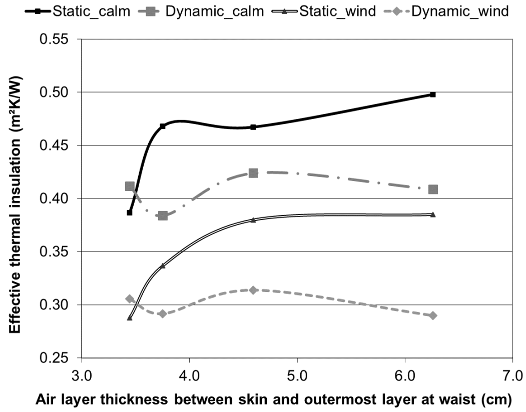

Figure 9: Effective thermal insulation (I_{cle}) on torso with mid-layer size M in relation to air layer thickness from inner surface of outermost garment to skin at waist.

The figure shows two different curve shapes, one for the static and one for the walking situations. In the static situations, including both calm and windy conditions, the measured I_{cle} tended to be higher when the outermost garment was larger, but in windy conditions, the I_{cle} reached its highest value and indicated no tendency to further increase. The second curve shape in figure 9 represents the walking situations in which the highest cusp of the I_{cler} was when the distance from the inner surface of the outermost garment to the skin was 4.7 cm. The I_{cler} was lower if the garment size was smaller or larger than at the cusp. In addition, higher I_{cler} was seen with the smallest outer garment, when the pumping effect caused by walking was diminished due to thin air layers inside the clothing. It was resulted that when the outermost layer was a size 52 and the mid-layer was a size M the thermal insulation reached its highest value in windy and moving conditions.

Effect of wind direction

The effect of wind direction on the static thermal insulation of the clothing system was evaluated by turning the thermal manikin to a 0°, 45°, and 90° angle to the wind. The effect of the wind on the I_{cle} was greatest when the body was at an angle of 0° to the wind, and smallest when the angle was 45° (Figure 10). The wind effect was the smallest when the direct contact surface with the wind was the smallest.

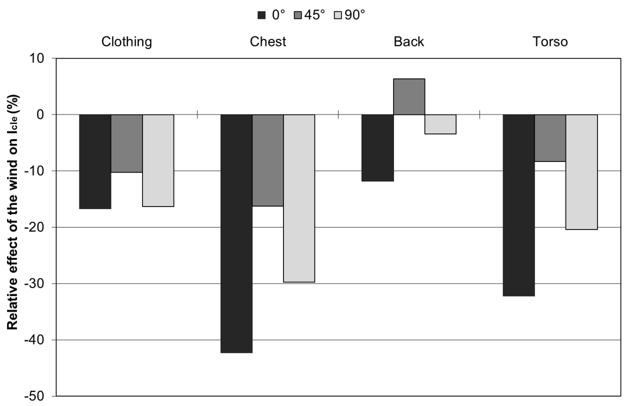

Figure 10: Relative effect (%) of wind from different directions (0°, 45° and 90° to the body) on effective thermal insulation (Icle) of clothing system (C3).

The thermal manikin was turned left side towards the wind at a 45° and 90° angle. Thus, the wind had a higher compressive and convective heat loss effect on the left side than on the right. Figure 11 shows the differences in the relative effect of the wind direction on the local I_{cle} values of the right and the left side of the body on the upper arm, forearm, thigh and shin.

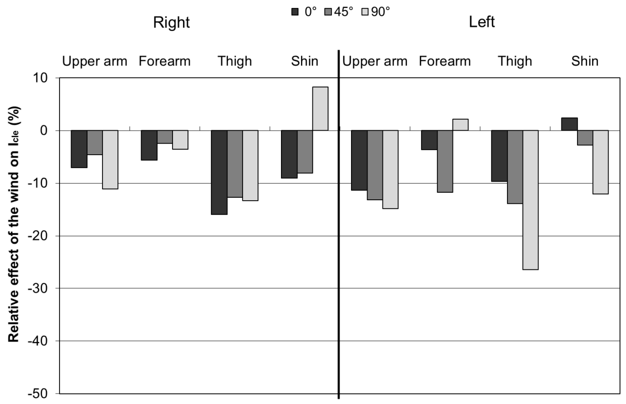

Figure 11: Relative effect (%) of wind direction on local effective thermal insulation (I_{cle}) values at right and left side on upper arm, forearm, thigh and shin.

The relative decrease of the local I_{cle} by the wind from the 45° angle on the left side was on average of about 10% (5.2) and on the right side about 7% (4.5). When the thermal manikin was at a 90° angle to the wind direction, the relative decline on the left side was on average about 13% (11.8) and on the right side about 5% (9.8).

The effects of wind direction were the most visible in the air gap movements on the waist area. When the wind direction was at a 45° angle to the body, the evaluation of the air gaps from cross-sectional figures on the waist area revealed that air content had increased on the right side of the body compared to the situation in calm conditions (Figure 12).

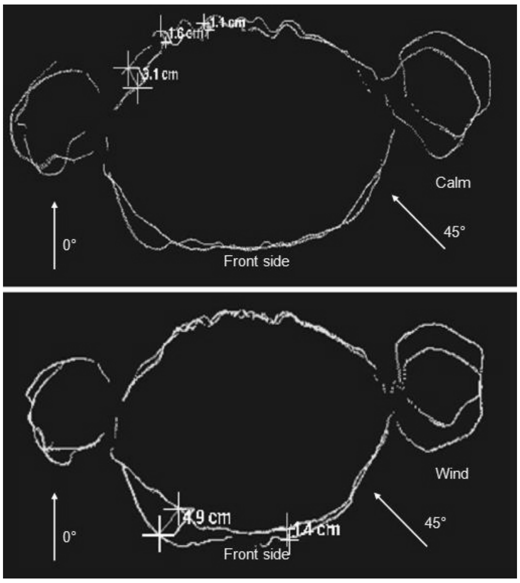

Figure 12: Cross-sectional pictures of waist when wind direction was 0° and 45° in calm (0.3 m/s) and in wind (8 m/s).

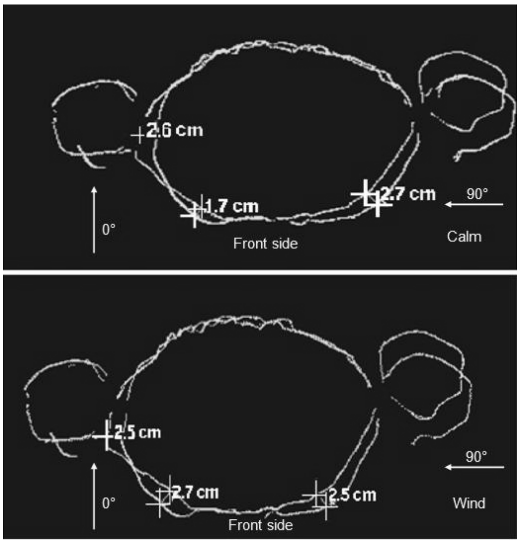

Figure 13: Cross-sectional pictures of waist when wind direction was 0° and 90° in calm (0.3 m/s) and in wind (8 m/s).

Similarly, when the wind was blowing from the left side (90° to the body), the air content was compressed on the left side, and greater on the right side (Figure 13).

Discussions

This study sought to find the optimum garment size of three-layered clothing systems in order to determine the highest possible thermal protection in cold, static, walking and windy conditions. In addition, the study examined the effects of different wind directions against the body on thermal protection in the cold. In our study we considered the optimum size of the three-layered cold protective clothing system, and therefore did not taking into account the possible effects of clothing size on the increased accident risk of garment grabbing for instance.

Thermal insulation of different sized clothing ensembles

In this study the effective thermal insulation (I_{cle}) and the resultant effective thermal insulation (I_{cler}) without the insulative boundary air layer around the ensembles were used to analyse relative changes in the intrinsic clothing insulation of the different clothing size combinations. Total thermal insulation (I_t) decreases greatly in windy conditions, due to the breakdown of the boundary air layer around the clothing surface. The thermal insulation of the boundary air layer (I_a) in calm condition (0.3 m/s) with the static thermal manikin was on average about 16% of the total thermal insulation and about 19% with the moving thermal manikin. The differences caused by the outermost and mid-layer clothing sizes were able to identify using effective thermal insulation without the effect of boundary air layer.

It has previously been shown that tight clothing fit has 6–32% lower insulation than loose-fitting clothing in wind speeds of 0.5 – 2 m/s [1-3]. In this study, tight clothing (size 48) provided on average about 17% lower effective thermal insulation in calm conditions and 13% lower in windy conditions (8 m/s) than the loose-fitting clothing (size 56). In calm conditions, static effective thermal insulation was higher when the outermost layer was larger in size. When the outermost garment was loosely fitting, the thermal insulative air layers were thicker under the clothing system providing higher effective thermal insulation. In this study the effect of different materials and fabric constructions on thermal insulation was eliminated by using same materials in each clothing ensemble. It was seen previously that the total thermal insulation differed by about 8% between three four-layered cold protective clothing systems developed for same purpose, but made from different conventional textile materials [25]. This suggests that clothing size may have relatively the same importance as choices of commonly used textile materials in layered clothing in evaluation of thermal insulation.

In windy conditions (8 m/s) the boundary air layer around the ensembles broke down due to high air movement. In addition, the wind compressed air layers and increased ventilation inside the clothing [2,7,8,10], thus decreasing the effective thermal insulation values. When the outermost clothing was the smallest in size the relative effect of the wind was greatest on the chest, due to almost total compression of the air layers underneath the clothing system. In contrast, when the clothing size was the largest, the relative effect of the wind increased due to convective heat loss by ‘chimney effect’ [26]. Furthermore, the relative effect of the wind was smaller in the lower body parts than in the torso. This is most probably due to the higher contact surface area of the torso with the direct wind, causing a greater compressive effect on the torso than on the lower part of the body.

Movement of the thermal manikin causes a ‘pumping effect’ underneath the clothing which means increased air exchange from the clothing to the ambient air. The effect then increases convective heat loss and decreases the thermal insulation of the clothing. [2, 8, 10] In previous study, it has been proposed that the effect of movement is smaller when the wind speed is higher [8, 12]. Anttonen and Hiltunen [12] found that a walking speed of 0.3–0.8 m/s decreased the total thermal insulation by about 10–20% in low wind speed (0.4 m/s) and about 5% in a wind speed of 18 m/s. The results of this study showed that the relative effect of body movement (walking speed 0.51 m/s) was on average higher in calm (17%) than in windy conditions (13%). This was seen when the two smallest outermost clothing sizes were used. Whereas, the relative effect of body movement was greater in wind with the two largest outermost garments and the effect was the highest with the largest outermost garments. Size M mid-layer provided the highest thermal insulation values in the wind and with movement. This indicates that a tight-fitting mid-layer creates a thick air layer between the mid- and outermost layers, in contrast to a loose fit between the mid- and base layers. An excessively thick air layer increases convection and the pumping effect under the clothing.

Measurements in calm and windy conditions using both a static and moving thermal manikin showed that effective thermal insulation values of the ensembles tended to be higher when the outermost clothing layer was larger. The relative decrease in the effective thermal insulation by wind, movement or their combination was the lowest when the outermost clothing was the smallest and the highest when the outermost clothing was the largest. The relative decrease in the static effective thermal insulation caused by wind was on average about 15%, and by movement about 17%. The combined effect of wind and movement decreased the effective thermal insulation on average about 26%.

Locally, the cusp of the effective thermal insulation of different clothing sizes was more visible. In wind and with movement, mid-layer size M provided the highest effective thermal insulation values on the torso, whereas outermost clothing size 52 provided the highest values and had the smallest relative effect caused by wind on the upper body in static situations. The selected base layer size was tight-fitting in the all ensembles. The clothing size of the thermal manikin was M or between 48 and 50, based on the girth measures of the chest and waist [20,21]. Thus the results infer that the optimum size of the mid-layer is similar to those recommended in the standard and that outermost clothing size should be one size larger than recommended.

The thermal manikin tests were performed in this study to be able to produce accurate and comparable results. The reproducibility of the thermal insulation test results in a single has shown to be good and the coefficient of correlation being lower than 3% [27]. The EN ISO 15831 standard [23] contains two different methods for calculating the thermal insulation of clothing ensembles; serial and parallel. Previous literature reveals that the serial method provides slightly higher thermal insulation values than the parallel method [28]. The mean relative difference between the methods in the static and resultant thermal insulation measurements [(static-resultant)/static] has been lower with the serial method than with the parallel method. The relative differences were evaluated as more significant when the distribution of the thermal insulation over the body was uneven [29]. This study only compared the thermal insulation values between the clothing ensembles, and evaluated the relative differences between the ensembles. Thus the calculation method used did not significantly affect the obtained results.

Air content in layered clothing

A previous study reported that thermal insulation increases linearly with the thickness of the air space until about 1.3 cm is measured between the two plates. After this, the insulation decreases due to convection caused by air movement in a wider air space [30]. A previous study showed that the highest thermal insulation value of one-layer clothing was obtained when the thickness of the air layer was 1 cm (corresponding to 7.5 cm difference in girth) in calm conditions and 0.6 cm (corresponding to 5 cm difference in girth) in wind at a speed of 2 m/s [1]. Another study proposed that with two-layered clothing, the highest thermal insulation value without a cooling effect caused by ventilation was obtained by having a distance of 2.3 cm between the body and outer garment on the chest [3]. In our study, the difference in girth was considerably higher, but this result is reasonable when taking into account that two layers of clothing were used underneath the thick outermost layer. The selected base layer size was tight-fitting in all the ensembles, and thus no space for an air layer between the body and inner layer existed. In this study, a size 52 outermost garment had about a 35 cm difference in waist girth (40% larger than body girth), and the distance from the inner surface of the outer layer was 4.7 cm. A size M mid-layer had about an 18 cm difference in waist girth (20% larger than body girth). Air layer thickness between each garment layer was calculated using Formula 5, which extracts the thickness of the fabric. This revealed that the air layer thicknesses were about 2.2 cm and 2.4 cm between the inner and mid layers, and mid and outer layers, respectively. The mid layer divided the air content inside the clothing into two halves between the inner and outer layers, when the inner layer was closely fitted to the skin.

The used software for 3D body scanning, provided accurate body girth measures of the different clothing layers. The software has not been commonly used in the evaluation of air gaps and air layer thicknesses, thus the method in this study was applied in a new context. To provide reliable results regarding the air gaps and layer thicknesses between garment layers, the 3D body scanning results were combined with the calculated air layer thickness values. The method provides solution to evaluate distribution of air gaps inside the clothing and to find the problematic areas of conductive heat loss or ventilation, which gives useful information for cold protective clothing development and design.

Effect of wind direction

The literature contains several studies of the effect of wind on heat transfer by convection [2,7,8]. In most of the studies, the wind has blown horizontally against the front side of the body, the equivalent to the 0° wind direction in our study. This study showed that the heat transfer mechanism was different in the left and the right side of the body when position of the thermal manikin was changed towards the wind direction. The 3D pictures revealed that the wind compressed the thickness of the air layers to the minimum on the left side, and thus the effective thermal insulation was decreased. On the other hand, the air layer thickness was increased on the right side and ventilation inside the clothing due to ‘chimney effect’ occurred. The relative decrease of the effective thermal insulation was about 10% and 13% on the left side and 7% and 5% on the right by the wind from the 45° and 90° angle, respectively. The decreased effect of the wind on the effective thermal insulation appeared to be smallest when the body was turned to a 45° angle to the wind direction and greatest when the wind was blowing directly against the body (0° angle). This seemed to be related to the contact surface area of the direct wind with the body, and thus, the compressed air layer underneath the outermost garments were smallest at a 45° angle to the wind direction.

Conclusions

This study determined the optimum garment size of different layers of three-layered clothing for maximum thermal insulation in the cold, as well as in walking and windy conditions. The results showed that the effective thermal insulation in calm conditions was greater when the mid- and outermost layers were larger in size. When air movement by wind (8 m/s) and movement of the thermal manikin were added, the effective thermal insulation on torso reached its highest value when the mid-layer size (difference in waist girth 18 cm) was in accordance with the recommendations of European standard EN 13402-3 (2004) and the outermost clothing size was one size larger (difference in waist girth 35 cm). If the air layer between the clothing layers increased more, the thermal insulation decreased, especially due to a pumping effect caused by walking. The relative effect of the wind was smaller in the lower body parts than in the torso. Wind had the least effect on effective thermal insulation when the body was at a 45° angle against the wind direction. This suggests that the exposed contact surface to the wind and thus the compressed air layer area underneath the outermost garments were the smallest at this wind direction.

The results of this study provide specific information for cold protective clothing development and design as well as manufacturers, retailers and end users on the optimum body girth looseness of layered cold protective clothing in order to obtain the highest possible thermal insulation. As a result, it is suggested that these results should be taken into account in standardization of protective clothing against cold. Future studies should investigate the optimum size of layered cold protective clothing in different body positions.

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List of Variables

AG = thickness of the air layer

I_a = thermal insulation of the boundary air layer measured with a stationary thermal manikin

I_{ar} = thermal insulation of the boundary air layer measured with a moving thermal manikin

I_{cle} = effective thermal insulation from skin to outer clothing surface measured with a stationary thermal manikin

I_{cler} = resultant effective thermal insulation from skin to outer clothing surface measured with a moving thermal manikin

I_t = total thermal insulation from skin to ambient measured with a stationary thermal manikin

I_{tr} = total resultant thermal insulation from skin to ambient measured with a moving thermal manikin

SD = standard deviation

Paper III

Kirsi Jussila, Anita Valkama, Jouko Remes, Hannu Anttonen, Ari Peitso

The Effect of Cold Protective Clothing on Comfort and Perception of Performance

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The Effect of Cold Protective Clothing on Comfort and Perception of Performance

Kirsi Jussila
Anita Valkama
Jouko Remes
Hannu Anttonen

Finnish Institute of Occupational Health, Oulu, Finland

Ari Peitso

Finnish Defence Forces, Centre for Military Medicine, Lahti, Finland

The physiological properties of clothing designed to provide protection against cold, windy and damp conditions affect comfort. The weight, thickness, stiffness of the fabrics and friction between the clothing layers affect physical performance. The comfort and perception of performance associated with 3 military winter combat clothing systems from different decades (the new M05 system, the previous M91 system and traditional clothing) were observed during a winter military manoeuvre. Subjective experiences concerning comfort and performance were recorded for 319 subjects using questionnaires. The most challenging conditions for comfort and performance were perspiration in the cold and external moisture. The new M05 system provided warmer thermal sensations ($p < .010$*), dryer moisture sensations in the presence of external dampness (*$p < .001$*), dryer perspiration moisture sensations (*$p < .050$*) and better perception of physical (*$p < .001$*) and mental performance (*$p < .001$*) than the other systems. Careful development of the clothing system guarantees good comfort and performance during cold exposure.*

cold protective clothing   clothing comfort   perception of performance

1. INTRODUCTION

Cold injuries have been a major issue even in recent military conflicts. Cold stress can cause local and whole-body cooling, which can lead to cold injuries and hypothermia. Performance, such as marksmanship, is negatively affected when core body temperatures are not between 36.5 and 37.5 °C [1]. Cold protective clothing has to provide protection not only against cold but also against windy and damp conditions at temperatures from above freezing point to extreme cold (–40 °C). The optimum total thermal insulation of the clothing system must be selected on the basis of the environmental conditions and physical work level, such as the weight, thickness and stiffness of the clothing, and the friction between the layers will affect physical performance and limit movement of the extremities. This research was carried out in the form of an observational questionnaire-based study administered during winter military training.

The hypothesis was that careful development of clothing materials and systems, taking into account

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Correspondence and requests for offprints should be sent to Kirsi Jussila, Finnish Institute of Occupational Health, Aapistie 1, FI-90220 Oulu, Finland. E-mail: <kirsi.jussila@ttl.fi>.

the user, tasks and environmental conditions, can guarantee good clothing comfort and performance during long-term exposure to cold weather.

1.1. Clothing Comfort

Clothing comfort is affected by the physiological properties of clothing, such as thermal insulation, water penetration properties and air permeability, and can be assessed in term of thermal sensations, the amount of external wetness and perspiration moisture. Comfort as experienced by the user can be influenced greatly by the protective properties of clothing against cold, wind and moisture and by the drying time.

Insufficient thermal insulation will lead to cooling of the body, whereas too high thermal insulation will result in sweating during physically demanding tasks. The size of the clothing and thickness of the air layer entrapped between the layers will affect both thermal insulation and the water vapour permeability of the clothing ensemble. Previous research has shown that thermal insulation and water vapour permeability increase with a thicker air layer, but there is obviously an optimum air layer thickness beyond which the values start to drop [2]. Thus the clothing must not be too small or too big. Size is very important when seeking to maximise protection against cold [2, 3].

It has also been shown that sweating reduces thermal insulation and that a dramatic fall in cooling efficiency occurs when moisture is absorbed from the skin before it evaporates [4, 5]. According to a recent study [6], fabrics that have a higher thermal insulation and air permeability, such as fleece, achieved a higher temperature and lower vapour pressure under cold conditions than a microporous membrane (MPM) fabric. The higher vapour pressure in MPM was attributed to condensation, which blocks the pores that transport water vapour [6]. It has been shown elsewhere that effective water vapour resistance increases greatly as the outside temperature decreases [7]. The amount of moisture absorbed is influenced by the properties of both the underwear and outer clothing.

The significance of air permeability is most pronounced at higher wind speeds and higher levels of physical activity, where heat loss needs to be increased. Air movements cause ventilation inside the clothing, which can be used to remove excess heat and water vapour [8]. The use of a combat vest and body armour will compress the clothing layers, reducing the thickness of the air layers and blocking air movements inside the clothing. Body armour and a combat vest will increase protection against wind but detract from the amount of moisture evaporating from the clothing.

Attempts have been made to reduce the weight of cold protective clothing to lighten the workload and improve performance, but little attention has been paid to the friction properties of military clothing. It has been shown that an increase in weight and the number of clothing layers will increase the work load [9, 10, 11].

1.2. Performance

Cold protective clothing increases the physical work load and energy expenditure, the weight of the clothing having the greatest influence, while its stiffness is the second most important factor. Friction between the clothing layers and the effect of thick clothing in hindering movement of the extremities add to the physical work load [9, 10, 11].

Mental performance has a substantial impact on orientation, safety, decision making, work efficiency and reactivity in demanding situations, and the physiological effects of cold exposure have a direct influence on mental performance. These effects can be seen even when no actual hypothermia can be diagnosed [12]. Cold conditions lengthen reaction times and increase errors in tasks that demand high levels of mental performance [13].

1.3. Objective

The objective of this research was to examine the effects of cold protective clothing systems from different decades on clothing comfort and perception of performance during 11 days of winter military training. The results obtained with the new clothing system were compared with two clothing systems from earlier decades.

2. MATERIAL AND METHODS

2.1. Cold Protective Clothing Systems

The newly developed winter clothing system of the Finnish Defence Forces (model 2005, M05) was assessed and compared with corresponding systems from earlier decades (model 1991, M91, and traditional coarse cloth). The same underwear was used with all the systems, and they all had a similar utilization rate. The specialities of the new M05 system include increasing adjustability of the thermal insulation and wind protection, higher resistance to water penetration and lower weight. Table 1 provides a more detailed description of the cold protective clothing systems. Figure 1 presents the combat clothing systems with the combat clothing as the outermost layer. Table 2 shows the physiological properties of clothing of the systems are given.

The middle layer clothing belonging to M05 is of a closer fit and stretches more than does M91 middle layer clothing, with the aim of reducing the impairment of movement due to clothing. A long zip from the neck to the hem of the middle layer shirt is used in M05 to facilitate the putting on and taking off of the shirt relative to the M91 shirt, where a short zip was used. The absorption properties of the middle layer clothing were improved by increasing the wool content. The wetting of the combat clothing layer was alleviated by reducing the amount of hydrophilic cotton in the cloth. The materials and fibre contents of the snow and cold weather clothing

TABLE 1. Descriptions of the Cold Protective Clothing Systems (M05, M91 and Traditional Clothing), Their Fabric Constructions and Fibre Content

Clothing Layers	M05	M91	Traditional Clothing
Underwear	2 × 2 rib knit (PES 50%, CO 33%, MAC 17%)	2 × 2 rib knit (PES 50%, CO 33%, MAC 17%)	2 × 2 rib knit (PES 50%, CO 33%, MAC 17%)
Middle clothing	shirt: terry knit (WO 70%, PA 30%) trousers: terry knit (WO 60%, PES 25%, PA 15%)	knitted fibre pile (PA 80%, PES 20%)	knitted fibre pile (PA 80%, PES 20%)
Combat clothing	satin weave (CO 50%, PES 50%)	satin weave (CO 65%, PES 35%)	felt (WO 85%, PA 15%)
Snow clothing	twill (PES 70%, CO 30%)	twill (PES 70%, CO 30%)	twill (PES 70%, CO 30%)
Cold weather clothing	outer fabric: twill (PES 70%, CO 30%) lining: taffeta (PES 100%)	outer fabric: twill (PES 70%, CO 30%) lining: taffeta (PES 100%)	outer fabric: twill (PES 70%, CO 30%) lining: taffeta (PES 100%)
Cap	single knit (WO 100%)	single knit (WO 100%)	single knit (WO 100%)
Facemask	fleece (PES 100%)	—	—
Gloves	1. leather 2. insert gloves: terry knit (WO 100%), technical side single knit (PES 100%)	1. leather 2. insert gloves: terry knit (WO 57%, PA 25%, PES 18%)	1. leather 2. insert gloves: terry knit (WO 57%, PA 25%, PES 18%)
Socks	1. liner: single knit (PP 20%, PA 30%,WO 50%) 2. winter sock: 5 × 1 rib knit, terry stitched inside, reinforced sole, heel and toes (WO 85%, PA 15%)	1. liner: single knit (WO 75%,PA 25%) 2. winter sock: 5 × 1 rib knit, terry stitched inside, reinforced sole, heel and toes (WO 85%, PA 15%)	1. liner: single knit (WO 75%, PA 25%) 2. winter sock: 5 × 1 rib knit, terry stitched inside, reinforced sole, heel and toes (WO 85%, PA 15%)
Felt lining for boots	felt (WO 75%, PA 25%)	felt (WO 75%, PA 25%)	felt (WO 75%, PA 25%)

Notes. PES—polyester, CO—cotton, MAC—modacrylic, WO—wool, PA—nylon, PP—polypropylene.

TABLE 2. Clothing Physiological Properties of the Clothing Systems (M05, M91 and Traditional Clothing)

Property	M05	M91	Traditional Clothing
Air permeability (L/m²s)			
combat clothing	33	53	160
cold weather clothing	7	5	5
Thermal insulation (m²K/W) without cold weather clothing layer			
dry	0.415	0.413	0.444
damp	0.383	0.390	0.414
Resistance to water penetration (Pa)			
combat clothing layer	2720	2190	2000

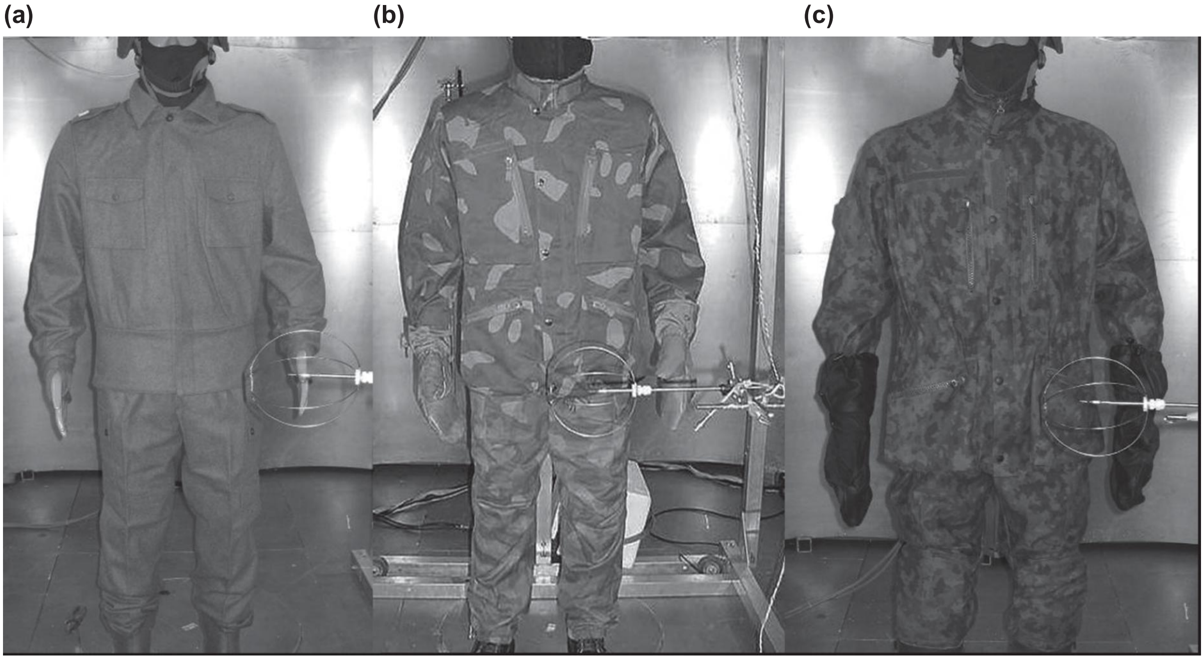

Figure 1. Clothing systems from different decades, when the outermost layer is combat clothing: (a) traditional clothing, (b) previous M91, (c) new M05.

layers remained the same, but their wetting was reduced with more efficient repellent finishes.

Protection of the face was enhanced with a face mask in M05, and the hands are now better protected from the wind and wet by means of an improved design of leather mittens. The structure of the knitted insert mitten has been altered by providing a separate forefinger to enable improved performance in military tasks.

The moisture transfer properties of M05 liner socks have been increased by decreasing the wool content. The winter boots in the M05 system have more efficient thermal insulation than the previous models and their rotational stiffness has also been increased. The M05 winter boots also contain breathing insoles.

The other reference clothing system, used in addition to M91, was traditional coarse cloth clothing. These two systems were otherwise similar except that traditional coarse cloth outerwear made of a dense felted material was replaced with combat clothing in M91 (Figure 1). The dense felted material has good air trapping properties and thickness, giving it good thermal insulation values but high levels of moisture absorbance and stiffness.

The total weight of the M05 winter clothing system was ~2 kg, or 10%, lower than that of the corresponding M91 clothing system. The greatest economies in the weight of the actual garments were achieved in the middle layer garments (–30%) and the cold protective clothing (–7%).

2.2. Field Questionnaires

Test subjects assessed the effects of the three cold protective clothing systems on human thermal and moisture protection and on physical and mental performance in long-term cold exposure during winter military training in northern Finland in December 2005. The training was divided into two parts, physically demanding combat training and combat shooting training. The clothing systems were not rotated between the users for practical and hygienic reasons in view of the long military manoeuvres carried out in the forest. The test subjects were healthy volunteers from among the male conscripts, average age 20 years; participation in the training and the clothing systems were distributed at random. Subjective experiences in terms of clothing comfort and physical and mental performance were elucidated using two daily questionnaires, a clothing questionnaire and a surveillance card. The data were analysed separately for the three clothing systems to enable comparison.

The clothing questionnaires were used to monitor the clothing used, the coldest thermal and general moisture sensations in different parts of the body, ease of using the middle layer clothing and the effect of clothing on survival and performance. Table 3 gives the generally used scales for the thermal [14] and moisture [15] sensations employed in the clothing questionnaire. The thermal sensation *very hot* was left out as being irrelevant in this case. The sensations were given in verbal form in the questionnaire. The detailed instructions about what to wear during training were prepared in co-operation with clothing experts from the Western Finland Logistics Regiment of the Finnish Defence Forces. The ballistic protection and armoury of all the test subjects conformed to regulations.

TABLE 3. Thermal [14] and Moisture Sensation [15] Scales Used in the Clothing Questionnaire

Thermal Sensation		Moisture Sensation	
very cold	0	*dry*	0
cold	1	*almost dry*	1
cool	2	*slightly moist*	2
slightly cool	3	*moist*	3
neutral	4	*almost wet*	4
slightly warm	5	*wet*	5
warm	6	*soaking wet*	6
hot	7		

Surveillance cards distributed and collected on a daily basis were used to allow the conscripts to evaluate their state of health, mental and physical performance, mood, motivation, stress level, nutrition and cold experiences, all on separate 10-point scales. The results were used in combination with those from the clothing questionnaires to assess the significance of the clothing used.

The questionnaires were distributed 11 times during the training and a total of 319 completed forms were obtained. Of the test subjects who answered daily, 10 were wearing M05, 7 the M91 clothing system and 12 the coarse cloth system. Some changes to the garment combinations used during the training were made by the users because of the weather and the activities to be performed. The winter combat clothing was worn on 41 occasions altogether and the ballistic vest 48 times, which contained 23 answers given by test subjects using M05 and 25 using M91.

Ambient conditions were measured throughout the training with a portable weather station (DAVIS Vantage Pro; DAVIS, USA) placed near the training area in the field and readings taken every 10 min. Weather information was also gathered from the Finnish Meteorological Institute’s weather station in Salla. Day time weather was calculated as the average of the measurements made between 6:00 and 18:00 and night time weather from the data measured between 18:00 and 6:00. Any major variations from the mean weather parameters were also taken into account when assessing the functioning of the clothing. Figure 2 summarises the ambient conditions during the manoeuvres.

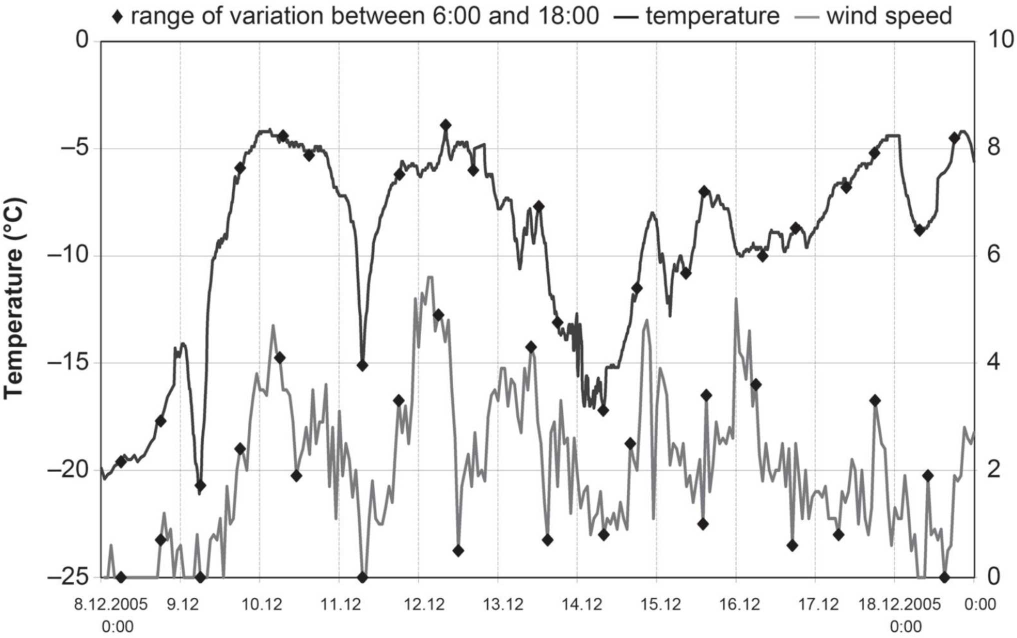

Figure 2. Wind speed and ambient temperature during winter military training. Daily highest and lowest ambient temperatures and wind speeds measured between 6:00 and 18:00.

2.3. Analysis of Questionnaire Data

The data were analysed statistically using SPSS version 15.0 for Windows. This enabled direct analysis of each question and cross-tabulation of the data. The test subjects were given code numbers in the database, so that their identities were not revealed at any stage in the research.

The independent samples *t* test was used to test differences in the means for two clothing system groups in terms of thermal sensation, experience of external moisture and perspiration sensation and for physical and mental performance. Means and standard deviations were calculated.

Percentage differences between the clothing systems for were analysed using the χ^2 test, and differences in measured values in the surveillance data were assessed with an analysis of variance (ANOVA) with repeated measures. The level of significance in all the statistical tests was taken to be $p < .05$.

3. RESULTS

3.1 Clothing Comfort

The test subjects' daily assessments of the coldest thermal sensations in the body are given in Figure 3. The mean value (*SD*) of the thermal sensations with M05 was 3.9 (1.7), corresponding to a *neutral* thermal sensation, the corresponding figures with the other systems being 3.3 (1.4) for M91 and 3.4 (1.6) for traditional clothing. The thermal sensations became warmer with drier moisture sensations (χ^2 test, $p < .001$).

Protection against cold and wind was experienced as significantly better with M05, as can be seen in Figure 4 (*F* test, $p < .001$). According to the daily clothing questionnaire, 62% of the test subjects using M05 considered the cold protection afforded by their clothing to be adequate, implying that the coldest thermal sensation of the day was *neutral* or warmer. The equivalent value for M91 was 46% and that for traditional clothing 45%.

Figure 5 presents the moisture sensations caused by snow, sleet or water with the different cold protective clothing systems. The mean value (*SD*) of the moisture sensations caused by external dampness when wearing M05 was 1.3 (1.2), corresponding to an *almost dry* sensation. The corresponding mean values for the other systems were 1.8 (1.5) for M91 and 2.1 (1.3) for traditional clothing. According to the daily clothing questionnaire, 66% of the test subjects using M05 considered their clothes to have been

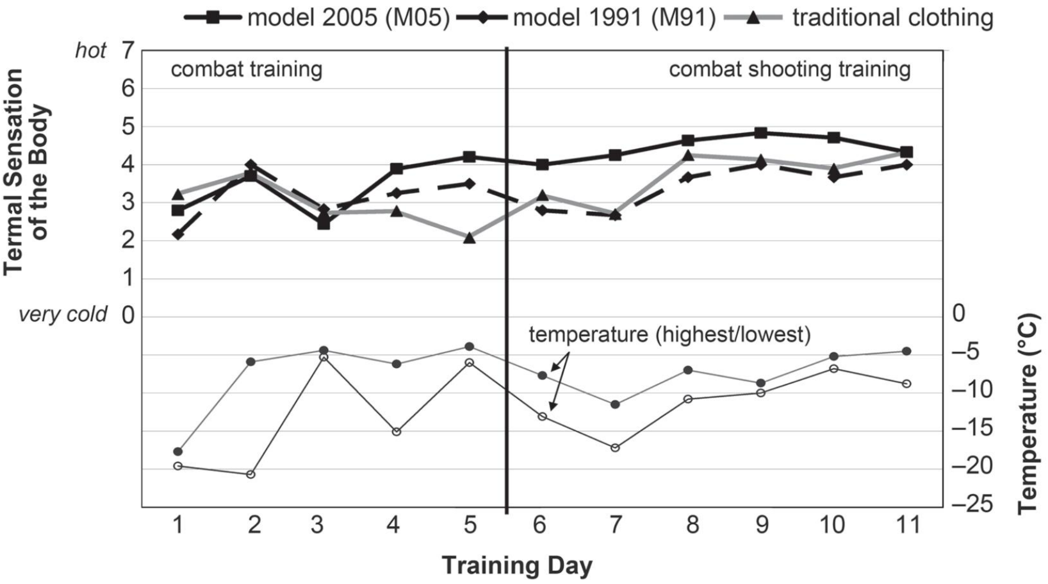

Figure 3. Coldest thermal sensations (mean values) experienced by test subjects in 3 winter clothing systems: M05 (N = 86), M91 (N = 39), traditional clothing (N = 99). Differences between clothing systems: F test, $p < .05$ (*ns*). Daily highest and lowest ambient temperatures measured between 6:00 and 18:00.

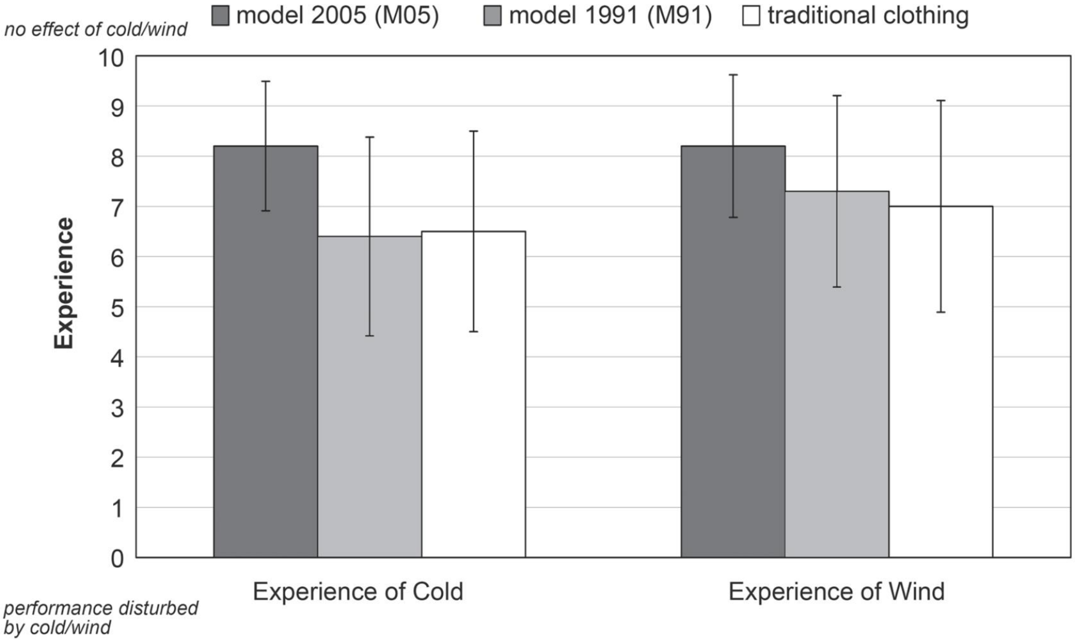

Figure 4. Protection against cold and wind ($M \pm SD$) as experienced by test subjects in different clothing systems: M05 (N = 110), M91 (N = 77), traditional clothing (N = 132). Differences between clothing systems: χ^2 test, $p < .001$.

dry or *almost dry* (values 0 or 1), as compared with 47% of those using M91 was and 31% for traditional clothing. There was a close statistical correlation (χ^2 test, $p < .001$) between the external moisture sensations and environmental temperature, implying that the clothing was considered damper in warmer than in colder weather.

Figures 6–7 present the moisture sensations caused by perspiration with the different cold

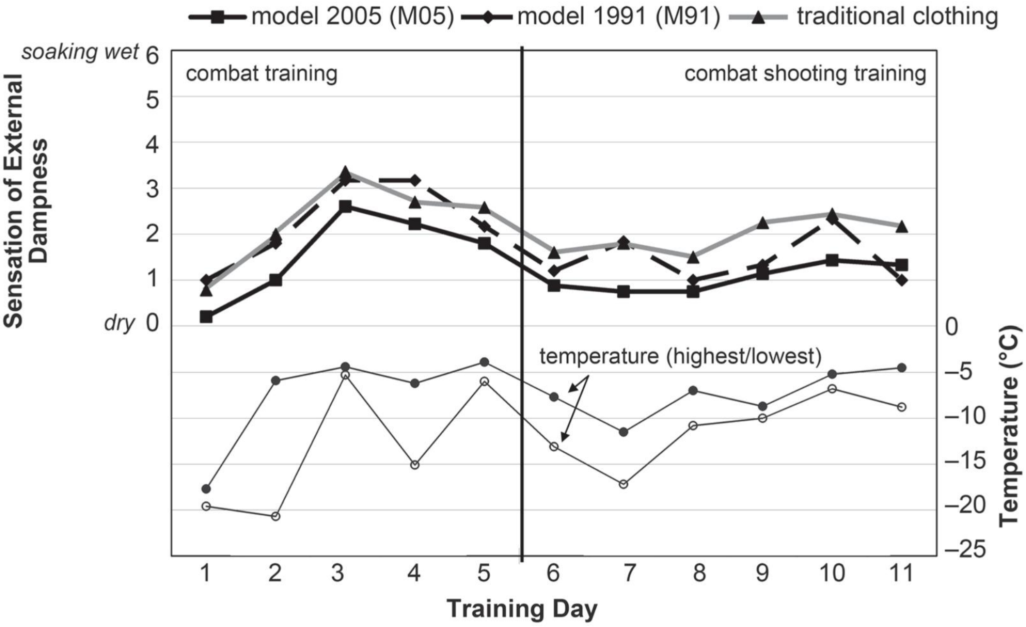

Figure 5. Moisture sensations caused by external moisture (mean values) as experienced by test subjects indifferent winter clothing systems: M05 (*N* = 88), M91 (*N* = 43), traditional clothing (*N* = 99). Differences between clothing systems: *F* test (*ns*). Daily highest and lowest ambient temperatures measured between 6:00 and 18:00.

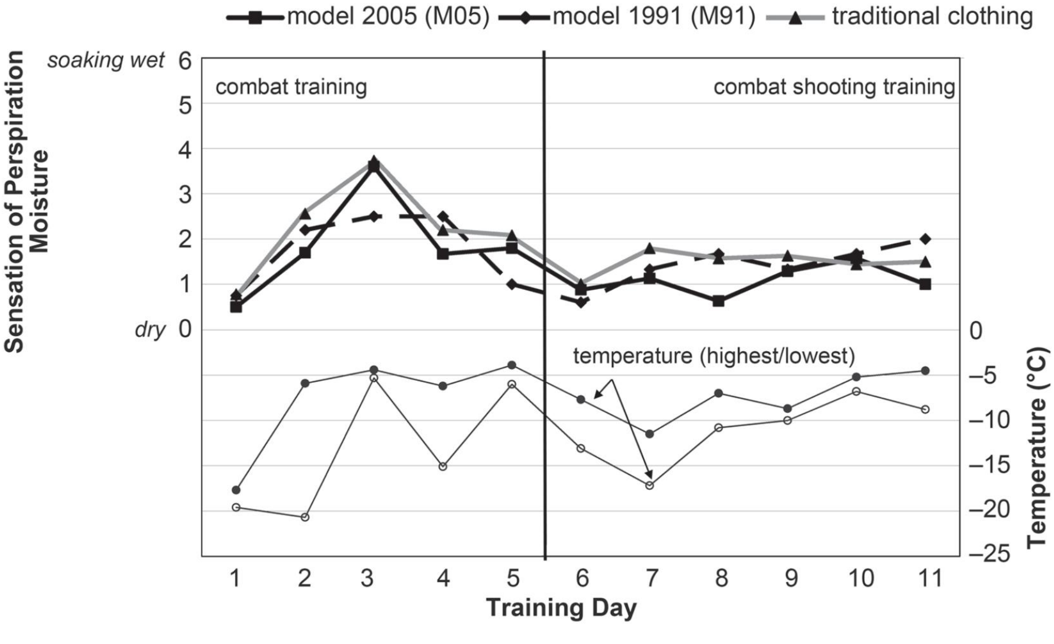

Figure 6. Daily variations in moisture sensations caused by perspiration (mean values) as experienced by test subjects in different winter clothing systems: M05 (*N* = 88), M91 (*N* = 41), traditional clothing (*N* = 96). Similar underwear was used with all systems. Differences between clothing systems: *F* test, *p* < .05 (*ns*). Daily highest and lowest ambient temperatures measured between 6:00 and 18:00.

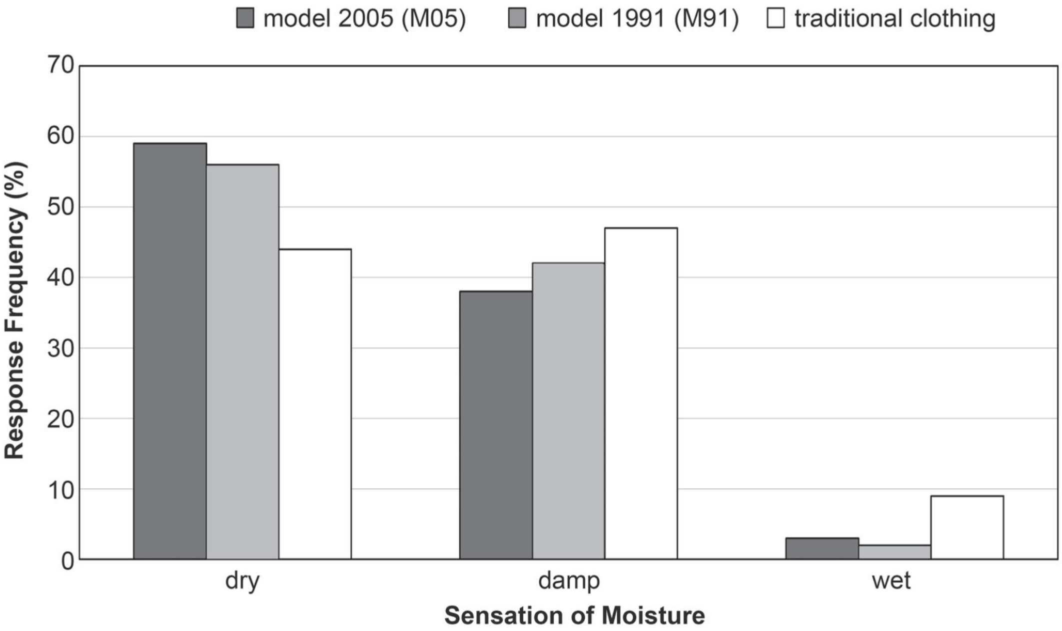

Figure 7. Moisture sensations caused by perspiration as experienced by test subjects in different winter clothing systems: M05 (*N* = 88), M91 (*N* = 41), traditional clothing (*N* = 96). Similar underwear was used with all systems. Differences between clothing systems: χ^2 test, *p* < .05 (*ns*).

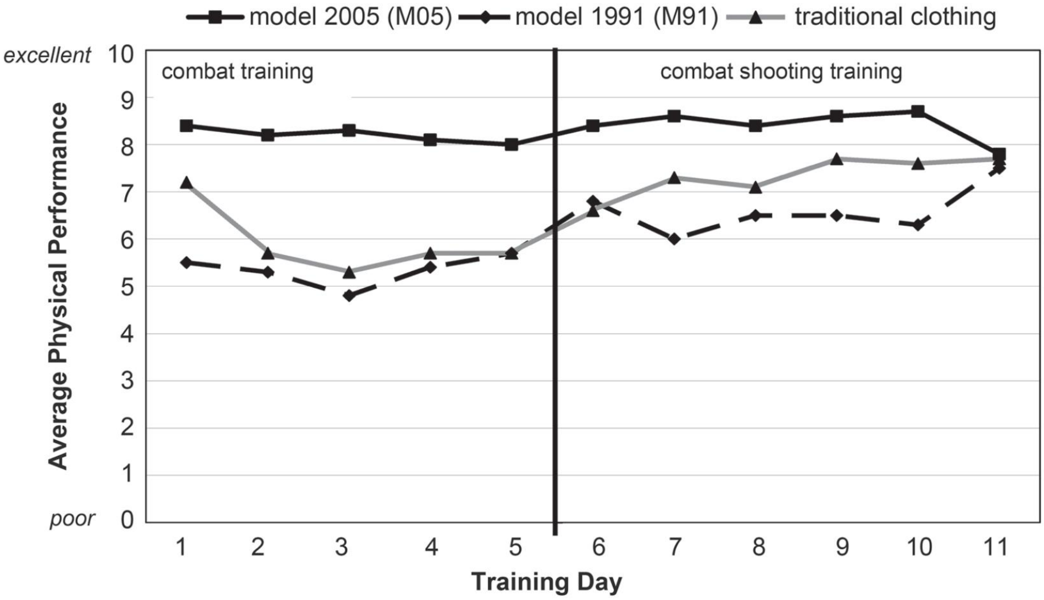

Figure 8. Perception of physical performance (mean values) as indicated in the daily clothing questionnaires by subjects using the different clothing systems: M05 (*N* = 110), M91 (*N* = 77), traditional clothing (*N* = 132). Differences between the clothing systems: *F* test, *p* < .001.

protective clothing systems. Figure 6 presents daily results. Similar underwear was used with all of the systems. The mean value (*SD*) of the moisture sensations caused by perspiration when wearing M05 was 1.5 (1.2), which corresponds to *almost dry* or *slightly moist*, while the mean value obtained with the other systems were 1.6 (1.3) for M91 and 1.8 (1.6) for traditional clothing.

3.2. Perception of Performance

The test subjects using M05 rated their physical performance higher in the daily questionnaires (*T* test, *p* < .001) than did the others (Figure 8), with a mean value (*SD*) of 8.3 (1.0) as opposed to 5.9 (2.1) for M91 and 6.8 (1.9) for traditional clothing.

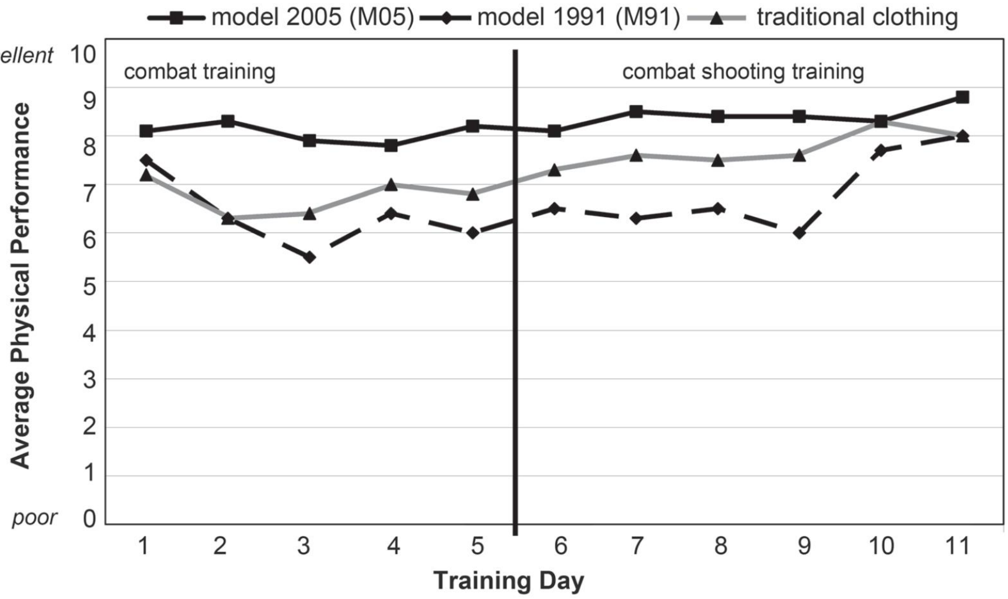

Figure 9. Perception of mental performance (mean values) as indicated in daily clothing questionnaires by subjects using different clothing systems: M05 (*N* = 110), M91 (*N*= 77), traditional clothing (*N* = 132). Differences between clothing systems: *F* test, *p* < .001.

Significant differences in perceptions of mental performance were also found between the test subjects using the different clothing systems (Figure 9), and there was a close correlation ($p < .001$) between the protective properties of the clothing (protection against both cold and moisture) and mental and physical performance. The mean value (*SD*) for perception of mental performance was 8.2 (1.3) with M05, 6.5 (2.4) with M91 and 7.3 (1.8) with the traditional clothing.

4. DISCUSSION

This assessment of the effectiveness of three different military cold protective clothing systems from different decades, the new M05 model, the previous M91 model and traditional coarse clothing, on clothing comfort and both physical and mental performance was carried out in long-term (11 days) cold exposure during winter field training in northern Finland. The most challenging environment was not the cold as such but a combination of cold with perspiration during physical activity, external moisture and wet snow.

The physiological and subjective results for the new M05 clothing system were more positive than for the other clothing systems from earlier decades. M05 gives sufficient protection to enable the user to maintain a good thermal balance under extreme cold conditions, and the thermal insulation and ventilation of the new clothing system is easy to adjust to prevent overprotection and the resulting sweating during the performing of physically demanding tasks under changing environmental conditions. The total weight of M05 is ~10% lower than of the previous cold protective clothing system, which improves the user's physical performance. M05 provided for warmer thermal sensations ($p < .01$), dryer moisture sensations in the presence of external dampness ($p < .001$), dryer moisture sensations caused by perspiration ($p < .05$) and better perceived physical and mental performance ($p < .001$) than the other cold protective clothing systems (M91 and traditional clothing). Equivalent results, that the fabric properties of cold protective clothing systems could significantly affect humidity and temperature distributions and comfort, have been shown in an earlier study [15].

If the thermal insulation of cold protective clothing is too low, the test subject will lose body heat to a harmful extent and the probability of frost damage will increase. According to earlier research, the values of thermal insulation are highest when the thickness of the air layer is 0.6–1 cm [2]. This required air layer thickness was obtained by using multiple (3–5) layers of clothing and choosing clothing of the correct size. Underwear must be snug, and the outer layers must not compress the layers underneath. It has been shown that sweating reduces thermal insulation proportionally to moisture retention [4] and that there is a dramatic fall in cooling efficiency when moisture is absorbed from the skin before it evaporates [5]. According to previous studies, energy consumption at work increases ~3–4% per clothing layer because of the weight of the layers and friction between them [10]. It has also been shown that the weight of the clothing causes a 2.7% per kg increase in energy consumption [11]. M05 is ~2 kg lighter than M91 and traditional clothing, and the middle layer in particular is more flexible, resulting in a smaller increase in load. These results are in line with other findings that thick, heavy, stiff clothing increases the physical load involved in performing tasks [9, 10, 11].

Relating to clothing comfort, M05 allows increased adjustability of the thermal insulation even though the total thermal insulation is similar to that in other systems. Experiences of cold and wind were examined on a daily basis, and it was evident that the test subjects wearing M05 were not affected by the cold and windy conditions during training as much as the other test subjects. The differences between the clothing systems were caused by the lower air permeability and higher resistance to water penetration of M05, which also preserved its thermal insulation properties better under difficult ambient conditions and during physical labour than the other clothing systems. Thermal sensations were closer to neutral when wearing M05 than the other systems except in the first 3 days of training, when the moisture sensations caused by external and perspiration moisture were also wettest, which directly affects thermal sensations. Also, on the third day of training, the level of physical activity was highest and the ambient temperature was warmer than on the other days. Traditional clothing was affected most by external moisture, on account of the hydrophilic nature of its cloth, with high wool content (WO 85%). Since all the test subjects were wearing the same underwear, the differences must have been caused by the absorption and wicking properties of the middle layer and the water vapour penetration properties of the outer layer. The middle layer clothing of M05 and M91 differs in terms of both material and fit, that of M05 fitting snugly and enabling quicker moisture transfer from the underwear.

M05 helped the test subjects to keep their thermal balance stable, resulting in less daily variation in perceived physical performance. The effect of the clothing on physical performance can be seen clearly in the day-to-day variation, the differences being greater during the physically more demanding combat training. The better water repellence of M05 kept it drier and meant that the decrease in thermal insulation was smaller than with the other clothing systems, and this may also have affected perceived mental performance. To account for the psychological effect of the new clothing on perceived performance two separate questionnaires were used, the clothing questionnaire and the surveillance card. The latter contained no questions referring to the clothing used, the emphasis being on other matters, such as state of health, mental and physical performance, mood, motivation, stress level, nutrition and cold experiences, the results of which were used in other ongoing research as well. In addition, the surveillance cards were distributed by the military personnel throughout the winter military training, whereas the clothing questionnaire was administrated by the researchers themselves. The clothing systems were not rotated between the users because of practical and hygienic issues associated with the long period of military manoeuvres in the forest. This means that the test subjects could not be asked to compare the clothing systems. However, the moisture sensations experienced on a daily basis on account of perspiration showed no significant differences between the three clothing systems, because similar underwear was used in all clothing systems. This shows that the new clothing had no psychological effect on the test subjects' sensations.

5. CONCLUSIONS

The physiological and subjective results for M05 were more positive than for the other clothing systems from earlier decades. The M05 winter clothing system gives sufficient protection to enable the user to maintain a good thermal balance under conditions of extreme cold. The thermal insulation and ventilation properties of the new clothing system are easier to adjust than those of the other systems to prevent overprotection and the resulting sweating during the performance of physically demanding tasks under changing environmental conditions. The total weight of M05 is lower than that of the previous cold protective clothing system, which partly enables improved physical performance on the part of the user. The results indicate that careful development of clothing materials and system, taking into account the user, the tasks to be performed and the environmental conditions, can guarantee comfortable sensations and good performance during exposure to cold weather.

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Paper IV

Kirsi Jussila, Sirkka Rissanen, Kai Parkkola, Hannu Anttonen

Evaluating Cold Protective Properties of Different Covering Methods for Prehospital Maritime Transportation – A Thermal Manikin and Test Subject Study

Prehospital and Disaster Medicine, 29(6) 2014 pp. 580–588

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ORIGINAL RESEARCH

Evaluating Cold, Wind, and Moisture Protection of Different Coverings for Prehospital Maritime Transportation–A Thermal Manikin and Human Study

Kirsi Jussila, MSc;[1] Sirkka Rissanen, PhD;[1] Kai Parkkola, MD, PhD;[2,3] Hannu Anttonen, PhD[1]

1. Finnish Institute of Occupational Health, Oulu, Finland
2. Navy Command Finland, Logistics Division, Turku, Finland
3. University of Oulu, Institute of Health Sciences, Oulu, Finland

Correspondence:
Kirsi Jussila, MSc
Finnish Institute of Occupational Health
Aapistie 1, FI-90220 Oulu, Finland
E-mail: kirsi.jussila@ttl.fi

Conflicts of interest: none

Keywords: body temperature regulation; Emergency Medical Services; hypothermia prevention; maritime conditions; thermal insulation

Abbreviations:
CC: control clothing
CO: cotton
DLE: duration limited exposure
LWC: layered winter clothing
MAC: modacrylic
PA: polyamide
PES: polyester

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Abstract

Introduction: Prehospital maritime transportation in northern areas sets high demands on hypothermia prevention. To prevent body cooling and hypothermia of seriously-ill or injured casualties during transportation, casualty coverings must provide adequate thermal insulation and protection against cold, wind, moisture, and water splashes.

Objective: The aim of this study was to determine the thermal protective properties of different types of casualty coverings and to evaluate which would be adequate for use under difficult maritime conditions (cold, high wind speed, and water splashes). In addition, the study evaluated the need for thermal protection of a casualty and verified the optimum system for maritime casualty transportation.

Methods: The study consisted of two parts: (1) the definition and comparison of the thermal protective properties of different casualty coverings in a laboratory; and (2) the evaluation of the chosen optimum protective covering for maritime prehospital transportation. The thermal insulations of ten different casualty coverings were measured according to the European standard for sleeping bags (EN 13537) using a thermal manikin in a climate chamber (-5°C) with wind speeds of 0.3 m/s and 4.0 m/s, and during moisture simulations. The second phase consisted of measurements of skin and core temperatures, air temperature, and relative humidity inside the clothing of four male test subjects during authentic maritime prehospital transportation in a partially-covered motor boat.

Results: Wind (4 m/s) decreased the total thermal insulation of coverings by 11%-45%. The decrement of thermal insulation due to the added moisture inside the coverings was the lowest (approximately 22%-29%) when a waterproof reflective sheet inside blankets or bubble wrap was used, whereas vapor-tight rescue bags and bubble wrap provide the most protection against external water splashes. During authentic maritime transportation lasting 30 minutes, mean skin temperature decreased on average by 0.5°C when a windproof and water-resistant rescue bag was used over layered winter clothing.

Conclusion: The selected optimum rescue bag consisted of insulating and water-resistant layers providing sufficient protection against cold, wind, and water splashes during prehospital transportation lasting 30 minutes in the uncovered portion of a motor boat. The minimum thermal insulation for safe maritime transportation (30 minutes) is 0.46 m^2K/W at a temperature of -5°C and a wind speed of 10 m/s.

Jussila K, Rissanen S, Parkkola K, Anttonen H. Evaluating cold, wind, and moisture protection of different coverings for prehospital maritime transportation–a thermal manikin and human study. ***Prehosp Disaster Med.*** 2014;29(6):580-588.

Introduction

Cold exposure can be fatal for an injured person, who is often immobile, and whose body is thus not able to sufficiently produce metabolic heat.[1] Circulatory and respiratory demands may increase, and as body core temperature declines, the casualty's condition may deteriorate.[2]

Previous studies of casualty coverings, thermal responses, and experiences in cold environments have been conducted for prehospital aeromedical,[3] ground,[4,5] and mountain rescue.[6,7] Maritime conditions, which are often cold, wet, and windy, demand a sustained prehospital effort to prevent body cooling and hypothermia. They also set requirements for the protective properties and functionality of prehospital coverings during boat transportation. Therefore, protective clothing, weather conditions, the level of injury, and the time used for transportation should be taken into account in maritime conditions.[8] A protective covering is required to provide sufficient thermal insulation, as well as protection against wind, humidity, and water splashes, and to ensure functionality in prehospital boat transportation. Information based on research into prehospital coverings in cold maritime conditions is lacking in the literature.

Thermal insulation defines resistance to dry heat loss by radiation, conduction, and convection and is mostly related to the ensembles' ability to retain air. It has been shown previously that the thermal insulation of casualty coverings, such as blankets and rescue bags, correlates with the thickness of the ensemble under low wind conditions.[9] A 2-layer construction of a casualty covering is thought to provide higher thermal insulation and to better restrict air movements in the bag than a 1-layer covering.[6] Correspondingly, it is suggested that the combination of a vapor-tight layer and dry, insulating layer is the most effective covering system for preventing hypothermia in a moderate wind and with wet clothing. This combination was shown to increase skin temperatures the most, to lower metabolic rate, and to provide good thermal comfort after covering a precooled person wearing wet clothing.[10]

In maritime conditions, convective heat loss due to high wind speed has a great influence on the thermal insulation of coverings during boat transportation. Wind can multiply heat loss by convection from the body[11] and increase the risk of frostbite and hypothermia. According to Henriksson et al, the insulation capacity of blankets and rescue bags at high wind speeds is best preserved by ensembles that are windproof and resistant to the compressive effect of the wind.[9]

During maritime prehospital transportation, casualties may be exposed to splashes and rain. Clothing may also be wet from water or body fluids. It has been shown that moisture reduces clothing insulation and that a dramatic increase in cooling efficiency occurs when moisture is absorbed from the skin before it evaporates.[12–14] Moisture in textile materials decreases their ability to retain air, and a considerable increase in evaporative heat loss from the body occurs.[14] Moreover, it has been shown that effective water-vapor resistance increases greatly as outside temperature decreases.[14,15]

Practical prehospital guidance for cold conditions often recommends that wet clothing should be removed, if possible,[16] or some recommendations advise adding a waterproof material layer in order to reduce evaporative heat loss.[17] It is proposed that both the removal of wet clothing and adding a vapour barrier substantially decreases evaporative heat loss from a casualty.[18] Other previous studies have focused in more detail on the effects of evaporative resistance and heat loss in, for example, sleeping bags. It is claimed that using an impermeable, nondetachable cover around a sleeping bag at subzero temperatures can lead to excessive moisture accumulation.[19,20] The use of a semi-permeable membrane in sleeping bags is beneficial in terms of reduced moisture accumulation.

The aim of this study was to determine the thermal protective properties of different types of casualty coverings and to evaluate which would be adequate for use under difficult maritime conditions. The study also aimed to evaluate the need of thermal protection of a casualty and to verify the optimum covering system for prehospital maritime transportation.

Methods and Materials

Study Design

The study consisted of two parts: (1) the evaluation and comparison of different protective covering systems in different ambient conditions; and (2) the verification of the protective system for maritime casualty transportation. The first part was carried out using a thermal manikin in the climatic chamber, whereas the second part was performed during authentic maritime evacuation and transportation training at the Gulf of Finland.

Evaluation and Comparison of Protective Coverings

Covering Systems—Ten different covering systems were divided into two categories: (1) flat coverings, such as blankets, reflective sheets, and bubble wrap; and (2) rescue bags, such as coverings similar to sleeping bags. The covering systems and their weights are shown in Table 1. The thermal manikin was dressed in a long-sleeved shirt and long-legged underpants (polyester (PES) 50%, cotton (CO) 33%, modacrylic (MAC) 17%), and calf-length socks.

Measuring Thermal Insulation—The thermal insulation of the different coverings was measured in a climate chamber (length 10.3 m × width 4.4 m × height 3.3 m) using an aluminum thermal manikin (Finnish Institute of Occupational Health, Helsinki, Finland) consisting of twenty segments (Figure 1). The thermal manikin was the size of an average male with a height of 176 cm and 1.89 m^2 body surface area. Surface temperature was set to 34.0°C (SD = 0.1°C).

The measurement setup was based on the European standard for sleeping bags.[21] The thermal manikin was in a supine position on a profiled steel plate (170 cm × 95 cm × 0.2 cm) simulating cold ground. The steel plate was on a plywood board (200 cm × 80 cm × 1.2 cm) supported 73 cm above the ground to allow air circulation.

The air temperature in the climatic chamber (SattGraph 5000, ABB, Sweden) was adjusted to -5°C, and two different wind speeds were selected, 0.3 m/s and 4.0 m/s. The higher wind speed was used only for measurements with dry ensembles. The wind conditions were provided by two fans (VN100-10-4-1850, DLK Ventilatoren, Schöntal-Berlichingen, Germany) with 100 cm wing diameter and independently adjustable frequency converters (SAMI GS, ABB, Sweden) placed one on the other. The thermal manikin's legs were facing towards a wind tunnel (6.7 m × 1.0 m × 2.0 m). To the front of the wind tunnel, three ambient air temperature sensors (YSI-405, ± 0.1°C, Yellow Springs Instrument Co, Inc, Ohio USA) and three wind speed sensors (TSI-8465-300, ± 0.5%, TSI Incorporated, Minnesota USA) were positioned at different heights from the ground: 0.2 m, 1.1 m, and 1.7 m. The ambient temperature and wind speed were measured and recorded (VEEPro, version 6.1, Agilent Technologies, California USA).

The effect of moisture, such as wet clothing, inside the covering was simulated by spraying 300 g of water evenly on the long-sleeved shirt and long-legged underpants before measurement started. In the other measurement, external moisture, such as rain and splashes, was simulated by sprinkling 2,300 g of water

Code	Coverings and Their Material and Design Information	Weight (g)
(1) Flat Coverings		
1B	One blanket (PES 100%, thickness 3.6 mm)	1,365
1B + RefS	Reflective sheet (one side aluminized, thickness 0.1 mm) underneath one blanket (PES 100%, thickness 3.6 mm)	1,577
2B	Two blankets (PES 100%, thickness 3.6 mm)	2,729
2B + RefS	Reflective sheet (one side aluminized, thickness 0.1 mm) underneath two blankets (PES 100%, thickness 3.6 mm)	2,941
RescB	Rescue blanket (medical fleece with micro porous membrane, thickness 2.4 mm)	1,175
BW	Bubble wrap (thickness 2.7 mm)	403
(2) Rescue Bags		
R1	Rescue bag 1: sleeping bag-like, medical fleece with micro porous membrane, hood, zipper closure, integrated mattress	4,510
R2	Rescue bag 2: thin cover with welt, handles, and integrated mattress	2,465
R2 + RefB	Reflective blanket (aluminized, honey comb structure, thickness 0.7 mm) underneath rescue bag 2	2,957
R3	Rescue bag 3: sleeping bag-like with hood and zipper closure, overlay material 100% PA (sport nylon 210 denier) with carrying straps; padding: 100% CO; lining: taffet textile	2,940

Table 1. Measured Casualty Covering Systems and Their Weight
Abbreviations: PES, polyester; PA, polyamide; CO, cotton.

on the upper surface of the covered thermal manikin. This corresponded with rainfall of 2 mm. The ambient temperature was set to -5 °C and wind speed to 0.3 m/s. The effect of the moisture on thermal insulation was monitored for four hours and measured using the ensembles presented in Table 1, excluding rescue bag 2.

The standard thermal insulation of the coverings was calculated using Formulas 1, 2, and 3,[21]

$$(1)\qquad R_c = \sum_{i=1}^{n} f_i \times R_{ci}$$

$$(2)\qquad f_i = \frac{a_i}{A}$$

$$(3)\qquad R_{ci} = \frac{T_{ski} - T_a}{H_{ci}}$$

where R_c is the standard thermal insulation (m^2K/W), f_i is the surface area factor of each segment, n is the number of independent segments, R_{ci} is the local thermal insulation of the segment (m^2K/W), a_i is the surface area of the segment (m^2), A is the total surface area of the manikin (m^2), T_{ski} is the temperature of the segment (°C), T_a is the air temperature (°C), and H_{ci} is the dry heat loss of the segment (W).

Verification of Protective Covering for Maritime Transportation

Protective Coverings—One of the measured coverings was selected as an optimum covering for casualty transportation in authentic maritime conditions, on the basis of its thermal insulation, protection against wind, moisture handling properties, and functionality based on laboratory measurements. Layered winter clothing (LWC) with rain clothing (0.53 m^2K/W) was used as control clothing (CC). Protective covering was evaluated together with LWC and compared with CC. Layered winter clothing consisted of a T-shirt, long-legged underpants, a turtleneck shirt, a woollen sweater, middle pants, a combat jacket and trousers, and a cold-weather padded jacket and trousers. Feet were covered with liner socks, felt linings, and winter rubber boots. Hands were protected with leather gloves, the head with a woollen hat, and the face in two measurements with a balaclava (PES 100%) and the rest without. All subjects had to wear a life vest on top of LWC or CC.

Experimental Procedure Test Subjects—Four healthy males volunteered to participate in the field measurements. The subjects were informed of the experimental protocol, and they gave their written consent to participate in the study. The experimental protocol of the study was conducted in accordance with the provisions of the Declaration of Helsinki, which describes international standards for human subject research, and the measurements were supervised by Kai Parkkola, MD, Surgeon General of the Finnish Navy.

The test subjects were between 18 and 20 years of age, and their average weight was 74.1 kg (SD = 4.8 kg). Each subject tested both ensembles in random order during the maritime transportation.

Experimental Procedure Measurements—The core temperatures of the test subjects were measured using a telemetric thermo capsule (Jonah Temperature Capsule, Respironics Inc, Murrysville,

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Figure 1. Measuring Thermal Insulation of Protective Coverings Using Supine Thermal Manikin on Metal Sheet

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Figure 2. Placement of Sitting Casualties Outside the Boat Cabin

Pennsylvania USA). The data were saved at 1-minute intervals by data loggers (VitalSense Monitor IP52, Mini Mitter Company Inc, A Respironics Inc. Company, Bend, Oregon USA). Skin temperatures were measured at ten sites (cheek, chest, upper back, upper arm, hand, finger, thigh, calf, foot, and toe) by thermistors (NTC DC95 Type 2252 OHM, Digi-Key, Thief River Falls, Minnesota USA). The thermistors were fixed onto the skin by flexible tape (Fixomull Stretch, BSN Medical GmbH & Co, Hamburg, Germany). These data were also saved at 1-minute intervals by data loggers (SmartReader Plus 8, ACR Systems, Surrey, British Columbia, Canada). Weighted mean skin temperature was calculated according to the ISO 9886 standard.[22] Relative humidity and the temperature between the lower and middle layers were measured using a sensor (OM-CP-Microtemp, Omega, Laval, Quebec, Canada). Thermal sensations were elicited according to the ISO 10551 standard.[23]

Air temperature was measured throughout the test by placing portable weather data loggers (iButton, DS 1921G-F50, ±1 °C, Thermochron iButton Device, Maxim Integrated Products, Inc, California USA) outside the boat cabin; these data loggers took readings every ten minutes. The wind speed was measured by a rotating vane anemometer (4.3405.20, ±2%, Thies Clima, Göttingen, Germany) and the speed of the boat was also recorded.

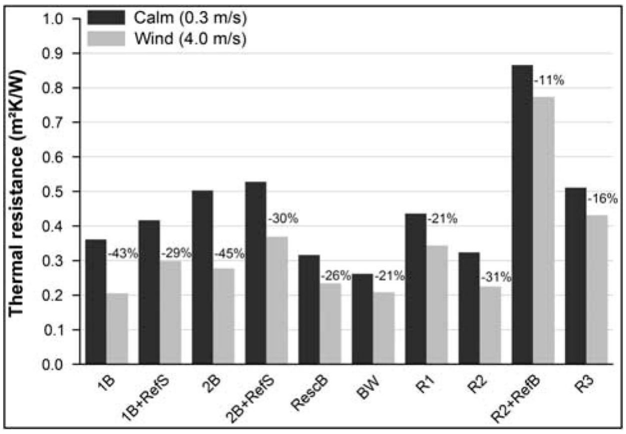

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Figure 3. Thermal Insulation of Different Coverings in Wind Speeds of 0.3 m/s and 4 m/s and Percent Decrease of Thermal Insulation Due to Wind

Protocol of Prehospital Transportation Measurements—The prehospital transportation exercise was carried out in November at sea in the Gulf of Finland. Those acting as walking casualties were transported by a partially covered motor boat for eight persons (Buster Magnum, Inhan Tehtaat Oy Ab, Ähtäri, Finland). The boat had been specially modified for maritime casualty evacuation in the offshore archipelago. The boat was 6.7 m × 2.4 m and the recommended engine size was 225 hp. The boat had three places outside the cabin for seated casualties as presented in Figure 2.

Before the boat transportation, the subjects were precooled for approximately 20 minutes on a pier wearing LWC or CC. The boat transportation started from the pier when the casualties were on the boat and dressed in the protective covering. Duration of transportation was 30 minutes, which is typical boat transportation time in the archipelago. Measurements ended after transportation when the boat arrived back at the pier.

Results

Evaluation and Comparison of Protective Coverings: Thermal Insulation

The standard thermal insulation of the measured ensembles varied from 0.26 to 0.87 m^2K/W (1.7-5.6 clo) in calm (0.3 m/s) conditions (Figure 3). A wind speed of 4 m/s increased heat convection from the coverings and thus decreased standard thermal insulation on average by 27% (SD = 11%). The thin, windproof, reflective sheet inside one or two blankets (1B + RefS and 2B + RefS) provided 33%-45% higher thermal insulation in the wind than the blankets alone (1B and 2B). The thick windproof reflective blanket with a honeycomb structure over rescue bag 2 (R2 + RefB) raised total thermal insulation in the wind by approximately 243% compared to that of the thin rescue bag 2 (R2) alone.

The local thermal insulation of the chest and back differed in calm conditions. Conductive cooling was stronger on the back

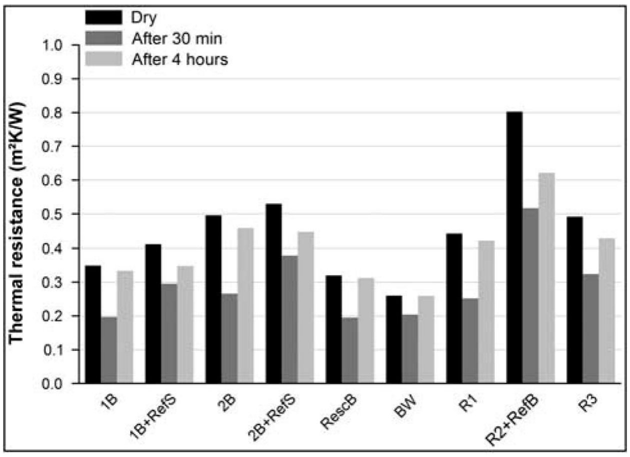

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Figure 4. Thermal Insulation of Coverings When Dry, 30 Minutes After, and 4 Hours After Spraying 300 g Water on Clothing Inside the Ensembles (Air Temperature = -5°C)

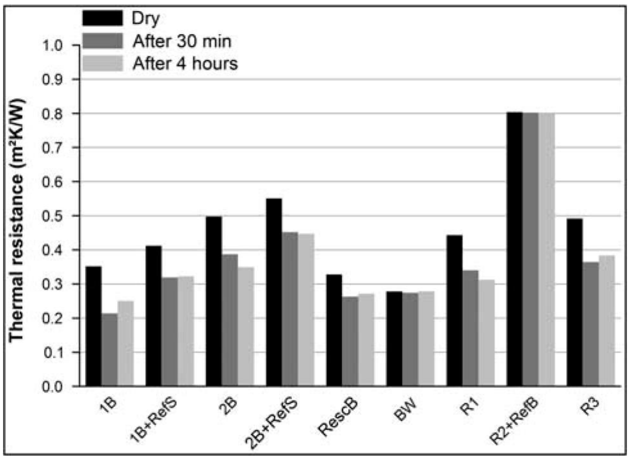

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Figure 5. Thermal Insulation of Coverings When Dry, 30 Minutes After, and 4 Hours After Sprinkling 2,300 g of Water on Surface of Ensembles (Air Temperature = -5°C)

due to the simulated cold ground (metal sheet) and compressed insulating covering fabrics. The rescue bags with the integrated mattress (R1 and R2) had exceptionally higher thermal insulation on the back than on the chest. However, only minor differences were found between the thermal insulation of the torso and legs in the studied ensembles.

The effect of wet clothing (300 g sprayed water) inside the coverings was seen in reduced standard thermal insulation, due to moisture transfer from clothing to the coverings 30 minutes after the water was sprayed (Figure 4). After this, drying occurred due to moisture evaporation. The added moisture resulted in a smaller decrease in standard thermal insulation when the reflective sheet was used underneath one or two blankets (1B + RefS and 2B + RefS). The standard thermal insulation of one and two blankets (1B and 2B) declined by 45% on average after 30 minutes. However, the decrease of standard thermal insulation was, on average, 29% with the reflective sheet inside the blankets (1B + RefS and 2B + RefS), and approximately 22% with the vapor-tight bubble wrap. The effect of moisture inside the rescue bags (R1, R2 + RefB and R3) decreased by 34%-43%, 30 minutes after the test had begun.

Four hours after the test began, over 90% of the sprayed water from the clothing had evaporated through one open-structured blanket (1B) and medical fleece with micro porous membrane (RescB), approximately 82%-85% through two blankets (2B) and medical fleece rescue bag with micro porous membrane (R1), and approximately 69% when a reflective sheet was used underneath the blankets (1B + RefS, 2B + RefS). In contrast, 31%-39% of the moisture had evaporated through the thin rescue bag inside the honeycomb structured reflective blanket (R2 + RefB) and the rescue bag with padding (R3) after measurements, and 51% through the vapor-tight bubble wrap.

The effect of external moisture was simulated by sprinkling water (2,300 g) on the surface of the coverings. The amount of unabsorbed water drippage just after sprinkling varied from 606 g to 1,901 g, depending on the moisture absorbency of the covering materials. Figure 5 shows that the effect of external water on the standard thermal insulation of the coverings was not as strong 30 minutes after sprinkling as that of the moisture inside the coverings (Figure 4). The thin rescue bag 2 inside the thick reflective blanket (R2 + RefB) and the water-tight bubble wrap absorbed the least water and thermal insulation remained at the same level during the 4-hour measurement. The standard thermal insulation of the other coverings decreased by 18%-39%, 30 minutes after sprinkling the water. After this, standard thermal insulation remained almost the same until the end of the measurement (four hours) and drying of the coverings did not occur.

Verification of Protective Covering for Maritime Transportation

Rescue bag 3 was the most optimum for casualty protection during prehospital transportation measurements in authentic maritime conditions on the basis of the comparative measurements performed in the laboratory. Its thermal insulation, protection against the wind, and functionality for prehospital boat transportation were the most suitable for these specific maritime conditions. The water-resistant rescue bag 3 consisting of padding was used on top of the LWC (LWC + R3).

Ambient Conditions—The ambient conditions were cloudy and occasionally rainy during the measurements. The measured ambient conditions are presented in Table 2.

Temperature and Humidity Inside Protective Coverings—The subjects (n = 4) wore CC or LWC during the precooling period on the pier (20 minutes). Control clothing included the rain clothing, whereas R3 was layered over LWC just before transportation began. The relative humidity between the lower and middle clothing layers remained dry (<50%) in both tested ensembles (Figures 6A and 6B). The temperature and relative humidity between the clothing layers declined during transportation when CC alone was used (Figure 6A), whereas relative humidity remained relatively constant during the measurement when LWC + R3 was used (Figure 6B). The temperature between the clothing layers increased slightly after R3 was added on top of LWC, and declined to the same level at the end of the transportation. At the end of the measurement, the temperature between the clothing layers was the same in both ensembles (30.5 °C).

	On the Pier	On the Boat
Air Temperature (°C)	1.0-2.0	0.5-2.0
Wind Speed (m/s)	0.0-1.5	–
Driving Speed (m/s)	–	10-13 (max 22)
Relative Humidity of Air (%)	25-90	100

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Table 2. Ambient Conditions During Boat Transportation Measurements

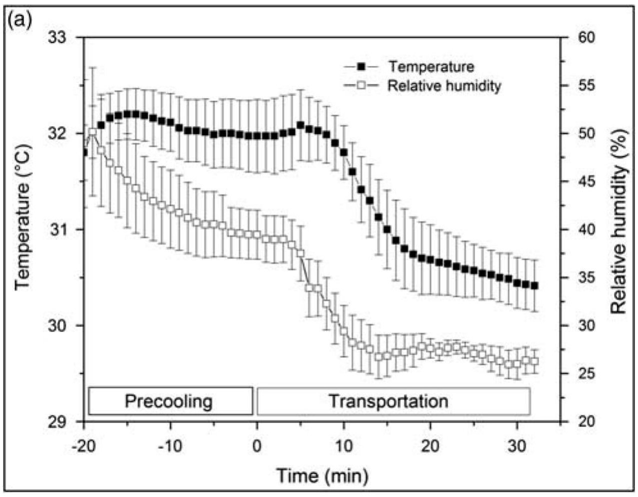

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Figure 6A. Mean Temperature and Relative Humidity Between Lower and Middle Layers with CC During Precooling and With LWC + R3 During Transportation
Abbreviations: CC, control clothing; LWC, layered winter clothing; R3, rescue bag 3.

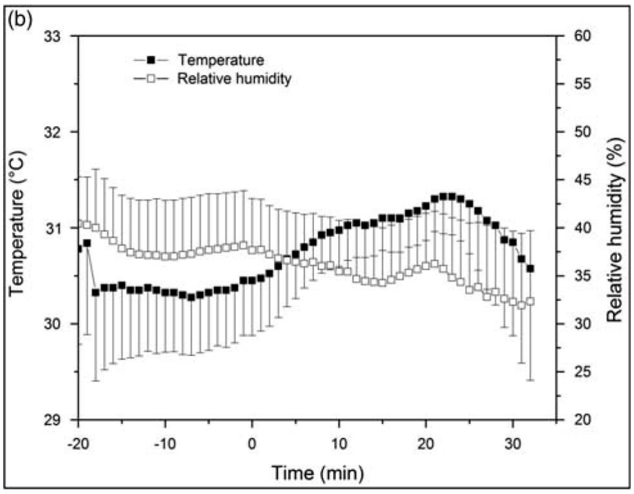

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Figure 6B. Mean Temperature and Relative Humidity Between Lower and Middle Layers With LWC During Precooling and With LWC + R3 During Transportation
Abbreviations: CC, control clothing; LWC, layered winter clothing; R3, rescue bag 3.

Physiological Measurements—Skin temperature decreased during approximately 30 minutes of maritime transportation by an average of 3 °C with CC, and 0.5 °C with LWC + R3 (Figure 7). General thermal sensation, before and after boat transportation, was "slightly cool." Core temperature increased during the precooling period on the pier, but at the end of the transportation, returned to the initial level with LWC + R3, and to slightly below the initial level with CC. Core temperature was 37.2 °C and 37.3 °C for LWC and CC, respectively, after the precooling period. After transportation, core temperature declined by 0.1 °C with LWC + R3 and CC.

At the end of transportation with CC, finger temperatures averaged 15 °C, the coldest temperature being 10 °C. Layered winter clothing + R3 maintained 6 °C higher finger temperatures at the end of the boat transportation than CC. Thermal sensations of the hands were "cold" with CC and "slightly cool" with LWC + R3 during transportation. Toe skin temperatures averaged 25 °C after the boat transportation, with both CC and LWC + R3. Similarly, thermal sensation on toes varied from "neutral" to "cold."

Cheek skin temperatures decreased below 15 °C and 12 °C with LWC + R3 and CC, respectively, when uncovered (Figure 8) because of the high air movement due to driving speed. Therefore, face protection by a balaclava was tested ($n = 2$): cheek skin temperatures remained constant, around 26 °C, during the measurement (Figure 8). Thermal sensations on the unprotected face were "cool" or "cold" during transportation, whereas sensations were "neutral" or "slightly cool" with the balaclava.

Discussion

During maritime prehospital transportation, it is essential to provide injured persons with thermal, wind, and moisture protection. When sitting, the subject is located outside the motor boat cabin, and is exposed to cold temperatures, high wind speeds, and water splashes. This study concentrated on the evaluation of different types of casualty coverings and on finding an optimum protective solution for injured persons exposed to maritime conditions while being transported by boat.

Evaluation and Comparison of Protective Coverings

Persons seated on an uncovered boat are exposed to high wind speeds. It has been shown that a moderate wind speed (3 m/s) decreases the thermal insulation of low insulation covers by 20% to 40%, and that of high insulation covers by 15% to 25%.[9] It has been shown that high wind speeds (12 m/s to 18 m/s) will decrease the thermal insulation of highly impermeable clothing ensembles by 30% to 40%. The decrease of the thermal insulation in wind is caused mostly because of boundary layer breakdown

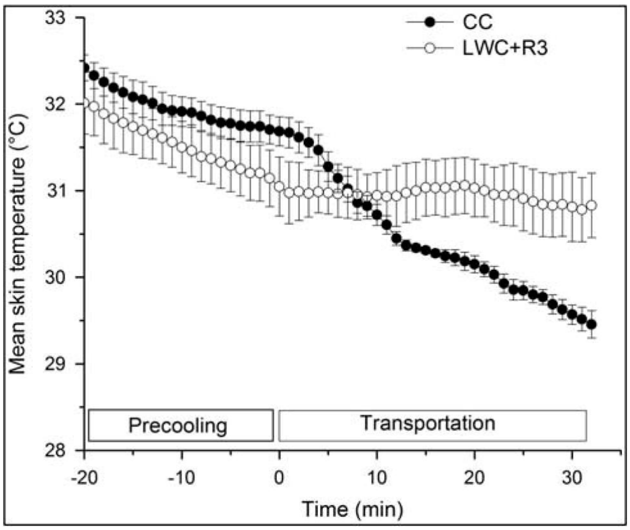

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Figure 7. Mean Skin Temperature During Precooling With CC and LWC, and During Transportation With CC and LWC + R3

Abbreviations: CC, control clothing; LWC, layered winter clothing; R3, rescue bag 3.

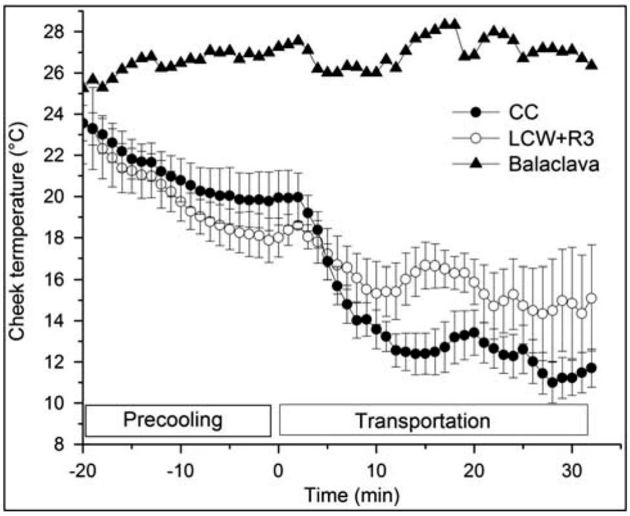

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Figure 8. Mean Cheek Temperature During Precooling With CC and LWC, and During Transportation With CC (n = 2), LWC + R3 (n = 4), and CC + Balaclava (n = 2) Abbreviations: CC, control clothing; LWC, layered winter clothing; R3, rescue bag 3.

and compression effects.[11] The results of the present study show that in windy conditions (4 m/s), thermal insulation of the windproof rescue bags decreased on average by approximately 20%. The thermal insulation of traditional blankets with lightweight and open fabric structures was reduced on average by 44%. Whereas when an additional reflective sheet was under the blankets, the decrease was on average 29%.

A recent study evaluated the thermal protection of bubble wrap and showed that it provided thermal insulation of 0.27 m^2K/W.[24] The result obtained in this study was similar to previous results. On the basis of the standard for sleeping bags,[21] the bubble wrap measured in this study provided only an adequate period of protection in ambient temperatures above 18 °C. The results of this study also show that bubble wrap maintains its thermal protective properties well in the wind and prevents evaporative heat loss. Both wind and internal moisture decreased the thermal insulation of bubble wrap by approximately 22%, and decreased that of the insulation of both one and two blankets by 45%, on average. These results correspond with the literature.[9]

Wet garments inside the coverings increased evaporative heat transfer from the skin. Therefore, the dry thermal resistance of the coverings declined. The ability of wet coverings to retain air is less and thus, thermal resistance decreased. Moisture may occur from an external source, such as rain, snow, and splashes, or from wet garments or bleeding. It has been shown that an evaporative barrier in prehospital covering prevents moisture from transferring to the outer layers of the coverings and thus reduces insulation capacity.[10] In this study, the effect of moisture inside the covering was examined by spraying the inner layer with 300 g of water. The blankets (1B and 2B) had an open fabric structure and therefore water vapor permeability was expected to be high. Thirty minutes after spraying, more water was absorbed from the clothing to the blankets, and further to the ambient air, than to coverings with vapor-tight material, such as reflective sheets or bubble wrap. Similarly, the decrease in thermal insulation was higher when blankets were used than when vapour-tight materials were added.

The influence of external moisture was evaluated by sprinkling 2,300 g water on the surface of the coverings. The water drippage from the coverings varied depending on the material construction and the properties, such as water resistance, of the different coverings. The blankets, being the outermost covering, absorbed more water than the bubble wrap, the water-resistant rescue bag with padding (R3), and the rescue blanket with micro porous membrane (RescB). This implies that bubble wrap, rescue bag 3, and a rescue blanket provide higher protection against splashes and moisture in maritime conditions. However, only minor moisture evaporation from the coverings was seen, even during a 4-hour measurement in cold ambient temperature (-5 °C). Thus, total thermal insulation remained at approximately the same level after four hours as after 30 minutes.

If a covering provides sufficient protection against cold, wind, and moisture, it is able to maintain the thermal balance of casualties in cold conditions during prehospital transportation from the accident site to a warm place. When these results were compared with the duration limited exposure (DLE) index based on standard EN ISO 11079,[25] it was seen that covering with an insulation value higher than 0.46 m^2K/W (2.94 clo) can provide sufficient protection for an immobile healthy person (58 W/m^2) for half an hour in -5 °C with high wind speed (10 m/s). In these ambient conditions, and for this exposure time, the thin rescue bag inside the honeycomb structured reflective blanket (R2 + RefB) and the water-resistant rescue bag 3 consisting of padding (R3) fulfilled the required protection due to their cold- and wind-protective properties.

Verification of Protective Covering for Maritime Transportation

Ambient conditions, such as cold, high wind speed, and water splashes, were simultaneously present in the authentic field measurements. Due to practical and financial reasons, it was only possible to test one covering ensemble and CC in these field conditions. Results from earlier studies have shown that the thermal insulation values of dry and moist clothing, defined using a thermal manikin, correspond well with wear trial values at moderate temperatures of 0 °C and -10 °C, and that the reproducibility of the test is good.[14,26-28] The results of the laboratory measurements were used to estimate the DLE in the expected ambient conditions during prehospital transportation. Based on the obtained results and functional properties, such as zipper closure and protective hood, rescue bag 3 (R3) was selected as the optimum covering for sitting casualties on an uncovered part of a boat.

During prehospital transportation in the uncovered part of the boat, wind speed was approximately 20 knots to 25 knots (10 m/s to13 m/s). In this situation, heat loss from the body to the ambient air increases.[29] In the present study, the temperature and relative humidity between the under and middle layers of the CC decreased rapidly after transportation began, due to the speed of the boat. This indicates that cold air got under CC through sleeve cuffs, legs, and the jacket hem, and thus conveyed warm air and moisture from the clothing. The rescue bag prevented air movement under the clothing through the jacket hem, cuffs, and legs. Thus, the temperature between the lower and middle layers in the rescue bag was 1 °C warmer for about 25 minutes of the transportation than without it. However, at the end of the transportation, the temperature between the clothing layers was approximately the same in both ensembles.

Thomassen et al[10] have studied the warming effect of three different prehospital wrapping systems on humans. There were significant differences between the systems in skin temperature, metabolic heat production, and thermal sensations, but not in rectal temperature.[10] This study showed that rescue bag 3 on top of LWC provided sufficient protection in the studied conditions (air temperature approximately 1 °C). Core temperature remained on average between 37.1 °C and 37.4 °C in both tested ensembles, which is within Lotens' "comfort" limits.[30] Skin temperature decreased by only 0.5 °C, which was approximately 31 °C during maritime transportation, whereas skin temperature while wearing CC declined by 3 °C, making it approximately 29 °C at the end of the measurement. It has been determined that the discomfort limit for the skin temperature of a healthy person is 31 °C and the tolerance limit is 25 °C.[30]

Wind and water caused strong cooling of unprotected skin. The rescue bag protected fingers and toes from cooling while the face was uncovered. Previous studies have found that cold wind on the face decrease the heart rate[31] and systolic and diastolic blood pressure.[32] In addition, it was found that cold wind on the face decreased blood circulation in the forearm by up to 22%.[31] Due to vasoconstriction in the present study, cheek temperature averaged below 15 °C and the thermal sensation was "cold." The use of an additional balaclava prevented cheek cooling, resulting in a 10 °C to 15 °C warmer temperature than without any cover. Hence, uncomfortable cold sensations and the possible occurrence of cold pain were avoided.

In this study, the subjects were healthy males. The tested protective solution provided sufficient protection against harmful cooling during transportation. It can be expected that cooling is more serious for an injured person than a healthy person. For example, hypovolemia accelerates the cooling of the body, especially of the extremities, due to impaired coagulation enzyme activity.[33]

Limitations and Future Research

The detailed laboratory tests were performed with 10 different prehospital coverings using the thermal manikin. It was not possible to cut the coverings for samples on the hot-plate tests, and therefore, water-vapor resistance was not able to be measured. Due to practical and financial reasons, it was only possible to validate the results of the one selected covering during authentic maritime boat transportation with four test subjects. The number of test subjects was set due to practical limitations of the training.

The tested rescue bag (R3) protected subjects against wind and water splashes by air- and water-tight material, and prevented air movement through sleeve cuffs, legs, and hems. However, putting the rescue bag on in the boat can be difficult due to injury and boat movement. Therefore, product development of cold protective coverings for casualties who are able to walk themselves should take into account the results of this study.

Conclusions

This study focused on prehospital protection of casualties during authentic maritime evacuation. Protection against cold, high wind speeds, and water splashes is required to prevent the cooling of casualties during prehospital boat transportation lasting approximately 30 minutes. The selected optimum rescue bag consisted of insulating and water-resistant layers providing sufficient protection against ambient conditions in the uncovered part of a motor boat. For casualties with wet clothing, it is also important to use a covering with vapor-tight material to avoid excessive evaporative heat loss. A rescue bag with thermal insulation of at least 0.46 m^2K/W (2.94 clo) is required to maintain the thermal balance of human casualties for half-an-hour of maritime transportation on an uncovered boat.

Acknowledgements

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Paper V

Kirsi Jussila, Erja Sormunen, Jouko Remes

Case Study: Perceived Usability of Emergency Communication Equipment with and without Protective Gloves in the Cold

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Case study: perceived usability of emergency communication equipment with and without protective gloves in the cold

Kirsi Jussila MSc(Techn)
Finnish Institute of Occupational Health

Erja Sormunen PhD
Finnish Institute of Occupational Health
University of Jyväskylä, Gerontology Research Centre and Department of Health Sciences

Jouko Remes MSc
Finnish Institute of Occupational Health

Primary Contact: Kirsi Jussila, Finnish Institute of Occupational Health, Aapistie 1, FI-90220 Oulu, Finland
Email: kirsi.jussila@ttl.fi

Abstract

Communication equipment must be usable at accident sites even in an extremely cold environment. The aim was to evaluate the effect of three different glove types on the use of different TETRA phones, and on finger dexterity in the cold (-20 °C). A VAS and SUS methods were used to evaluate the usability features of the phones. Finger dexterity tests in the cold were carried out to evaluate the effect of gloves on manual performance. Results showed that the type and material of the glove affected the usability features of the phones such as the use of push-buttons and tangent buttons, changing communication group, overall handling, and the compatibility of phone with the glove ($p<0.05$).

KEYWORDS: TETRA phone, Gloves, Cold, Dexterity, Usability.

Introduction

Communication is an essential part of rescue operations. Communication technology, for example, should improve performance and effectiveness in day-to-day rescue service operations (Hainbuchner, 2005). The TETRA digital radio communication system, based on the Terrestrial Trunked Radio standard, is widely used by public safety services and other governmental organizations in Europe, and in many other countries throughout the world. The system provides simultaneous voice and data transfer. Technically, TETRA phones resemble civilian mobile phones, but they must be usable at the site of accidents in all environmental conditions (Hainbuchner, 2005; Valajärvi, 2007). In cold weather conditions, being able to maintain usability and efficiency during a rescue operation becomes a crucial factor.

Manual performance in the cold is affected by cold temperatures, contact with cold surfaces, and the wearing of gloves (Bishu & Kim, 1995; Geng et al., 2006; Havenith et al., 1995). A previous study showed that working bare-handed in extreme cold conditions for more than a few minutes diminishes manual performance (Rogers & Noddin, 1984). Although gloves greatly reduce the risk of hands cooling, they inevitably affect dexterity (Havenith et al., 1995). A protective glove should allow as much dexterity as possible. Factors affecting dexterity relate to the glove material, such as its thickness, elasticity, deformability, as well as to the shape of the glove itself (SFS EN 420+A1, 2010; Tanaka et al., 2010).

Usability can be defined as the extent to which a product can be applied by specified users to achieve specified goals with effectiveness, efficiency, and satisfaction in a specified context of use (SFS EN 9241-11, 1998). In this context, effectiveness can be defined as the degree of success in dealing with a product. Efficiency refers to the time needed to carry out a task with the product, whereas satisfaction means a positive attitude towards the use of the product (Jokela, 2010). User friendliness (ease of use), technical support and training, i.e. organizational facilitators, are important supporting mechanisms for users' acceptance of a device (Hainbuchner, 2005).

A recently ended project called The Cooperation for Safety in Sparsely Populated Areas (CoSafe, 2011) addressed the issues related to the safety of people living in rural and sparsely populated areas of the Northern periphery countries. The project explored new and improved methods of managing major accidents and disasters in areas with difficult transportation infrastructure, inadequate telecommunications and extreme weather conditions. The project focused on the survival and well-being of disaster victims through effective on-site pre-hospital care, from the scene of an accident to the hospital. This case study was part of the CoSafe project, which aimed to evaluate the effect of three different glove types on the use of different TETRA phones in the cold (-20.0 °C). A further aim was to find the effect of different glove types on finger dexterity in warm (+26.5 °C) and cold (-20.0 °C) conditions.

Material and methods

The study consisted of two parts: usability tests of the TETRA phones, and finger dexterity tests in both warm and cold conditions.

Usability tests

Testers

Four male rescuers in the Northern Finland volunteered as test users for this study. The number of test users was selected on the basis of previous studies (Virzi, 1992; Nielsen & Landauer, 1993), which have shown that 80% of usability problems are detected by four or five testers. The testers' average work experience was five years and nine months (standard deviation, SD, ± six months). They were all experienced TETRA phone users. Three of the four men were left-handed. The average measure from the top of the middle finger to the end of the palm was 19.3 cm (SD ± 1.5 cm).

Material

The testers evaluated three different TETRA phones, P1, P2 and P3 (Figure 1). These phone models are typically used in one Rescue services district in Finland. Their dimensions and weights are shown in Table 1. The average weight of the phones was 279 g (SD 9 g).

Figure 1. Tested TETRA phones: P1, P2 and P3

Table 1. Dimensions and weights of tested TETRA phones

Property	P1	P2	P3
Height (mm)	133	147	133
Width (mm)	54 (handle) / 61 (screen area)	57	58
Depth (mm)	36	35	31
Perimeter (mm)	180 (handle) /194 (screen area)	184	178
Weight (g)	288	270	278

The usability tests were performed using three different glove types: firefighters' leather gloves, firefighters' leather/textile gloves, and work gloves (Figure 2 A–C, Table 2), as well as bare hands, during a simulated communication situation. The work gloves were of various different styles of leather gloves with lining. The size of the gloves was selected on the basis of the size of the users' hands.

Figure 2. Firefighters' leather gloves (A), firefighters' leather/textile gloves (B), and work gloves (C)

Table 2. Materials used in different gloves

Glove	Material	Thickness (mm)
Leather glove	Outermost material: Leather (calf, reindeer), knuckle protection Inner lining: Nomex Cuff: split leather Moisture barrier: Porelle membrane	3.5 (glove) 1.4 (leather)
Leather/textile glove	Inside, back of hand: special nappa calfskin Finger joint, knuckle protection, palm area and thumb interior: PBI gold elastic knitted fabric Inner lining: close-meshed knitted, 100% Kevlar Cuff: cracked calf leather Moisture barrier: Porelle membrane Reflective strip (25 mm) on cuffs	4.5 (glove) 2.1 (leather)
Work glove	Outer material, hand and cuff: Leather or textile Fabric lining	variation between 3.5 - 4.3

Test procedure

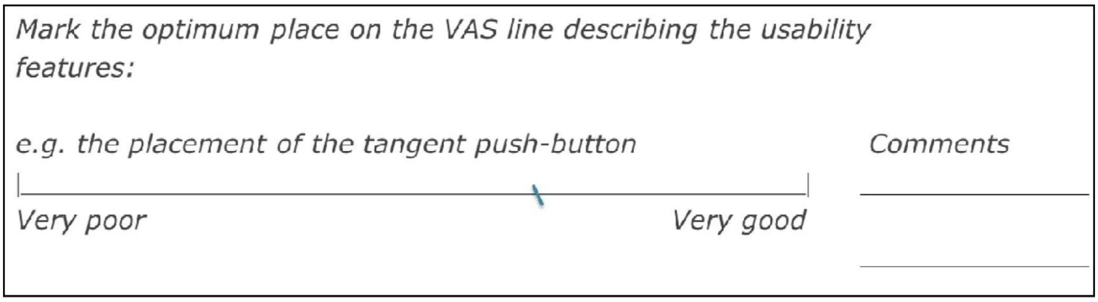
The usability tests were performed as simulated communication situations. Each tester performed the simulation with three different phones using three different glove types as well as bare handed. The situations were set in random order. The testers were allowed to use the TETRA phones beforehand, in order to become familiarized with them. Before the tests, the phones were placed in the chamber to cool. The simulated communication situation was controlled, and instructions were given by phone. The tests were performed in two separate climatic chambers at –20.0 ºC (± 0.3 °C) and at a wind speed of 0.3 m/s. The controller of the simulation was outside the chambers to avoid audibility from the same room. The simulation included the following tasks: responding to a call, conversing by phone, changing the communication group two different ways, and adjusting the volume. The testers indicated when the task was completed. The time used for each task was not recorded systematically, as the length of the conversations during the simulation varied. The simulation lasted between five and eight minutes.

The testers stayed inside the chamber during the tests, their physical workload being very light, about 75 W/m^2 (ISO 8996, 2004). They were wearing firefighters' protective gear with a long sleeved shirt and long-legged thin trousers and their own underwear. The thermal insulation of the protective gear was about 3 clo (0.47 m^{2}K/W) (Jussila & Anttonen, 2011).

Measurements

Visual Analogue Scale (VAS)

After the simulated communication tasks, modified visual analogue scales (VAS) were used to determine the usability features of the three different phone types (Price et al., 1983; Beauchamp, 1999; Nevala & Tamminen-Peter, 2004; Lintula & Nevala, 2006; Toivonen et al., 2011). The VAS is a 100 mm long continuous line with endpoints anchored by 0 (very poor) and 100 (very good). The VAS score is a measured distance (expressed in millimeters) from the 0 scale point. The participants were asked to mark on the line the point that indicated their evaluation of the following features: fit for hand, the shape and weight of the phone, the placement of the tangent push-button, the shape of the push-buttons, the clarity and size of the screen, screen update in the cold, changing communication group, audibility of the speaking voice, volume control and compatibility of phone with gloves. An example of the VAS questionnaire is presented in Figure 3. In addition, an overall evaluation of the phones and overall functionality were carried out. The questions were prepared in co-operation with experienced rescue service professionals.



Mark the optimum place on the VAS line describing the usability features:

e.g. the placement of the tangent push-button

Comments

Very poor

Very good

Figure 3. An example how the participants marked (\) on the 100 mm long continuous line the point that indicated their evaluation of the usability feature

System Usability Scale (SUS)

The global view of system usability with respect to the TETRA phones was evaluated using the System Usability Scale (SUS). The statements covered the following aspects of system usability: training, complexity, and need for support. System usability was presented as the theoretical percentage of 'perfection' on a scale of 0 to 100. The SUS questionnaire is regarded as a valid tool for usability assessment (Brooke, 1996).

Order of Superiority and Free Comments

The testers were also asked which TETRA phone they would rate the best, second best, and third best in the case of a disaster (Lintula & Nevala, 2006). All of the free comments regarding the usability of the phones were taken into consideration. The tests were videotaped.

Statistical analysis

The data are presented as mean values and standard deviation (SD). The Shapiro-Wilk test was used to test the normality for the data. For normally distributed variables, the parametric One-way analysis of variance (ANOVA) was used, followed by Bonferroni post hoc tests to test the equality of the mean values of the VAS scores between each situation. For non-normally distributed variables, the Kruskall-Wallis, followed by the Mann-Whitney post hoc test was used. The differences were considered statistically significant if $p<0.05$. The SPSS software (version 18) was used for statistical analyses.

Finger dexterity tests

Material

The glove types were the same as those used in the usability tests (Table 2). Three right hand gloves of each type were tested. The gloves were somewhat already used, i.e. not new. They were conditioned for 20 hours before measurements in test conditions.

Test procedure

The finger dexterity tests with different gloves were performed according to the standard SFS EN 420 + A1 (2010) with minor modifications: tests were conducted in both warm (+26.5 ℃) and cold (-20.0 ℃) conditions by one experienced tester according to the standard.

The tests were performed with five centerless ground stainless steel test pins. The tester picked up a pin by its circumference between his gloved forefinger and thumb without any other means of assistance (Figure 4). The same pin had to be picked up three times within 30 seconds without undue fumbling. The pins were 40 mm long and 5 mm, 6.5 mm, 8 mm, 9.5 mm and 11 mm in diameter. They were not conditioned before testing. The tester was kept in thermal balance during the tests by sufficient clothing and by breaks between tests in warm conditions. The result value, i.e. level of performance (Table 3) corresponds to the smallest diameter of pin that was picked up according to the test procedure. The results are given as means (± SD) of each different glove type (n=3 per glove types).

Figure 4. Finger dexterity tests with different gloves using five test pins

Table 3. Levels of performance in finger dexterity test (SFS EN 420 + A1, 2010)

Level of performance	Smallest diameter of pin fulfilling test conditions (mm)
1	11
2	9.5
3	8
4	6.5
5	5

Results

Usability tests

As there were no statistically significant differences in the functional features of the phones when used bare handed, the results were presented as mean values of all phones (pooled data), as well as separately (Figure 5A-D). The pooled data showed that the different glove types affected the usability assessments of the phones (Figure 5A).

The data from each phone separately (Figure 5B-D) showed that, in general, the usability of the push-buttons of the phones differed significantly depending on whether they were used with different gloves or bare handed. For each feature, the usability of the phones was evaluated as best when the firefighters' leather gloves were used compared to situation when the other gloves were worn. The poorest usability values resulted from the use of the leather/textile glove. The usability of the tangent push-button when P1 and P3 were used with gloves differed significantly from that when they were used bare handed. Correspondingly, significant differences in changing communication group were found when P2 and P3 were used. P3 differed significantly in all usability features depending on whether it was used with either different gloves or bare handed, with the exception of fit for hand.

It is noteworthy that the use of volume control of P1 was better with all tested glove types than bare handed (Figure 5B). The volume control of P1 was in the form of a roller, whereas the volume control of P2 and P3 was by push-buttons.

The SUS scores for P1, P2 and P3 were 51, 81, and 77, respectively. As regards communication in extreme cold conditions, three out of the four testers chose P2 as the best communication device in the case of a disaster, while one tester preferred P3.

P1 was considered the least suitable for communication in disasters in the cold by 50% of the testers. The free comments revealed that cold stiffened the push-buttons and tangent buttons, making the operation more difficult.

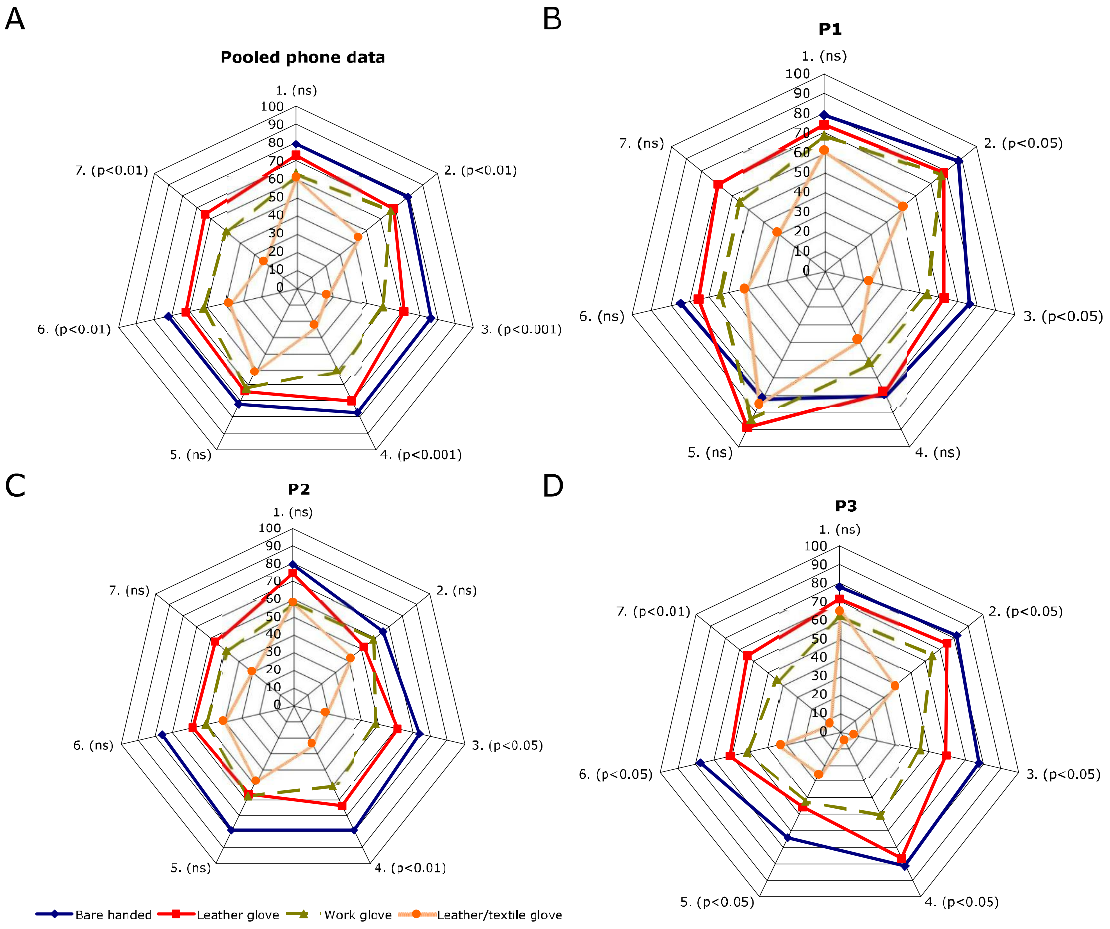


Figure 5. Mean values of perceived usability (visual analogue scale, from 0 = "very poor" to 100 = "very good") of TETRA phones with different gloves as rated by rescuers (n=4) after simulated tasks. Significant difference, $p<0.05$, ns = not significant. Numbers in figure: 1 = Fit for hand, 2 = Use of tangent push-button, 3 = Use of push-buttons, 4 = Changing communication group, 5 = Volume control, 6 = Overall handling, 7 = Compatibility of phone with gloves.

Finger dexterity tests

Table 4 presents the mean level of finger performance (± SD) according to the finger dexterity tests with different glove types in warm (+26.5 ℃) and cold (-20.0 ℃) climates.

The best level of finger performance both in cold and warm conditions was maintained with the firefighters' leather glove. The glove consisting of both leather and textile decreased the level of performance most at both temperatures. The cold decreased the average level of finger performance by about 0.7 - 1.0 compared to warm conditions.

Table 4. Results of finger dexterity tests, n=3 per glove types

Glove	Level of performance (mean ± SD) at +26.5 °C	Level of performance (mean ± SD) at -20.0 °C
Leather glove	3.3 ± 1.0	2.3 ± 1.3
Work glove	2.7 ± 1.4	2.0 ± 1.8
Leather/textile glove	1.2 ± 1.1	0.4 ± 0.9

Discussion

This case study focused on the use of communication equipment in rescue operations in cold conditions. In these cases it is important to simultaneously guarantee the usability of phones and to maintain the finger dexterity of the firefighter or first responder. The best possible match between the product and its users can be achieved by evaluating the product within an authentic or simulated operating situation with real users (Pheasant, 1996). In our study, the phones were tested in simulated operations. The study was planned together with researchers and experienced rescue service professionals, enabling us to identify the work tasks that required the use of a TETRA phone and to choose proper testing methods. The time used for each task was not recorded systematically, as the length of the conversations during the simulation varied. Four experienced males volunteered as test users for the usability tests. The number of test users was selected on the basis of previous studies (Virzi, 1992; Nielsen & Landauer, 1993; Spielholz et al., 2001). The small number of testers means that the results of this case study cannot be scientifically generalized. However, the results do demonstrate the tendency of practical results in extreme cold conditions in sparsely populated areas.

The use of gloves affects manual performance (Bishu & Kim, 1995; Havenith et al., 1995). The present results support previous studies by showing better usability of phones when used bare handed than with gloves. The lowest temperature in which it is possible to maintain practical bare-handed performance for more than a few minutes is –18 °C (Rogers & Noddin, 1984), a person should be able to use a communication device in extreme cold conditions while wearing protective gloves. The firefighters' leather gloves were perceived as the most suitable for use with the TETRA phones. The leather gloves also provided better dexterity than the other gloves in both warm and cold temperatures. The overall thickness of the leather gloves (including leather and lining) was less than that of the other gloves. The thickness of the glove has a strong negative correlation with finger dexterity (Havenith & Vrijkotte, 1993).

The test gloves were somewhat already used, and we assumed that a dirty glove stiffens more in the cold than a clean glove. The work gloves were of various styles, which caused high standard deviation in the dexterity results. Furthermore, information regarding the bending stiffness of the glove materials in the cold would give more detailed, precise knowledge of the effect of gloves on finger dexterity and on the usability of communication devices when wearing the gloves. If the duration of the tests had been longer or if the testers had been cooled before the test, the effect of cold on their finger dexterity would have been even more significant.

As regards the SUS scores and order of superiority of the phones, P2 was chosen as the best communication device in the case of a disaster in the cold, while P1 was considered as the least suitable. However, P1 had the highest average VAS values in fit for hand, use of push-buttons, tangent and volume control, and overall evaluation. The compatibility of the phone with the gloves was highest when P1 was used with each glove type. P1 was also rated the best with different glove types in the overall handling of the phone and the use of the push-buttons. The volume control of P1 was in the form of a roller, and was thus evaluated as being easier to use with gloves than P2 and P3, in which volume was controlled by push-buttons.

However, the compared TETRA phones varied only slightly in size and weight. P1 was barely heavier and had more depth and a longer perimeter than the other phones. In addition, the phones somewhat differed in shape and in the placement and depth of the push-buttons, and these variations presumably led to the differences in usability when gloves were worn. A recent study (Herring et al., 2011) demonstrated that as the handle perimeter of the hand-held tool decreased, the handle became less preferred when using layered gloves.

The SUS system is an effective and reliable tool for measuring the usability of a wide variety of products. Bangor et al. (2009) compared the SUS and a seven-point adjective-anchored Likert scale (N = 964), and found that the Likert scale scores correlate well with the SUS scores (r = 0.822). Thus in the present study, P2 (SUS score 81) and P3 (SUS score 77) were rated acceptable for system usability; P1 was in the margin of not acceptable (SUS score 51).

The VAS method has been used in several studies (Price et al., 1983; Jensen et al., 1986; Nevala & Tamminen-Peter, 2004; Lintula & Nevala, 2006). The ratings were originally used as outcome variables when back symptoms were analyzed in geriatric care. In recent studies, however, the method has been modified to evaluate various topics of interest (Lintula & Nevala, 2006). Although a questionnaire to evaluate the usability of mobile phones exists – the Mobile Phone Usability Questionnaire (MPUQ) (Ryu & Smith-Jackson, 2006) – it consists of six parts and 72 questions, and we considered it too wide for our study.

The study provides information for device development, by finding the most significant factors of the TETRA phones when they are used in the cold. However, detailed information on the use of the communication devices in long-term cold exposure is still needed. Factors such as finger mobility and material elasticity should be taken into account in the development and design processes of protective gloves for firefighters and first responders.

Conclusions

Communication is an essential part of rescue operations work. In cold conditions it is important to simultaneously guarantee the usability of the phone and the manual and finger performance of the rescue worker. This study aimed to evaluate the effect of different glove types on the use of Tetra phones and dexterity in cold conditions.

The perceived usability features of the tested TETRA phones did not differ significantly when they were used bare handed. The phones only slightly differed in size, shape, and the placement and depth of push-buttons. Volume control in the form of a roller was evaluated as being easier to use than push-buttons. However, the most significant differences in usability features were found when the different gloves were worn during the use of the phones. These differences were in the use of push-buttons and the tangent, in changing communication group, in overall handling, and in compatibility of the phone with the gloves. The firefighters' leather gloves were perceived as the most suitable for use with TETRA phones. They provided better dexterity than the other gloves in warm and cold temperatures.

The results of this study provide information on the properties of communication devices and protective gloves that will help to support the optimum selection of communication equipment and protective gloves for rescue services in cold weather areas.

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Tampereen teknillinen yliopisto
PL 527
33101 Tampere

Tampere University of Technology
P.O.B. 527
FI-33101 Tampere, Finland

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