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Physiological Strain and Physical Burden in Chemical Protective Coveralls

by

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ABSTRACT

This research draws together textile fabric and garment testing used in the prediction of human comfort in chemical protective clothing (CPC) with human wear trials. Four interrelated studies were performed to characterize and predict the thermo-physiological strain and physical burden in selected ISO Type 3, 4 and 5 chemical protective coveralls. In the first study, comfort in the CPC was evaluated through bench-scale sweating hotplate and Kawabata testing. Thermal and physical comfort was predicted using total heat loss values and multi-axis radar graphs that summarized the characterized mechanical properties from the Kawabata tests. The second study utilized three-dimensional body scanning and thermal sweating manikin testing to further assess the clothing ergonomics and thermal discomfort of the selected coveralls at the garment level. The full-scale thermal and evaporative resistances obtained from the sweating manikin tests correlated with the fabric results from the sweating hotplate. In the third study, significantly different physiological responses (i.e., oxygen consumption, heart rate, core and skin temperature and minute ventilation) and subjective comfort perceptions (i.e., rating of perceived exertion, hotness and wetness in clothing and restriction to movement) were determined in three selected coveralls through the controlled wear trials. In the fourth study, eight statistical regression models were developed through correlation and multiple regression analyses between the human responses and the results from the fabric and garment tests. These models showed that CPC increased physical burden by adding weight and/or by restricting movement. Oxygen consumption was predicted with clothing weight and fabric bending hysteresis. Fabric evaporative resistance and thickness were the two most significant predictors for the thermo-physiological responses, including change in body temperatures, change in heart rate and the physiological strain index. Fabric evaporative resistance and thickness were also the most significant predictors for average hotness, wetness and exertion perceptions during the test. The results of this research provide a better understanding of the influence of CPC on human thermo-physiological and physical comfort. The models developed enable textile researchers to predict the CPC effects on worker’s performance and comfort and will contribute to the development of more comfortable chemical protective garments.

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LIST OF ABBREVIATIONS

AAGS:	average air gap size
ASTM:	American Society for Testing and Materials
Bending-B:	bending rigidity per unit length
Bending-2HB:	moment of bending hysteresis per unit length
CBRN:	chemical, biological, radioactive and nuclear
Compression-LC:	compression linearity
Compression-RC:	compression resilience
Compression-WC:	energy required for compression
CP:	chemical protective
CPC:	chemical protective clothing
DMPC:	dynamic moisture permeation cell
HIC:	hotness in clothing
HR:	heart rate
ISO:	International Organization for Standardization
KES:	the Kawabata Evaluation System
mph:	miles per hour
NFPA:	National Fire Protection Association
PSI:	physiological strain index
R_{ct}:	fabric thermal insulation
R_{ct-c}:	clothing thermal insulation
R_{et}:	fabric evaporative resistance
R_{et-c}:	clothing evaporative resistance
RPE:	rating of perceived exertion
RTA:	restriction to arms
RTL:	restriction to legs
Shearing-G:	shear stiffness
Shearing-2HG:	hysteresis at shear angle of 0.5°
Shearing-2HG5:	hysteresis at shear angle of 5°
Surface-MIU:	mean value of coefficient of friction
Surface-MMD:	mean deviation of coefficient of friction
Surface-SMD:	mean deviation of surface roughness
T_c:	core temperature
Tensile-LT:	tensile linearity
Tensile-RT:	tensile resilience

Tensile-WT:	tensile energy per unit area
THL:	total heat loss
T_{sk}:	weighted mean skin temperature
t_{05}:	thickness at 5 gf/cm^2
$\dot{V}_E$:	minute ventilation
V_m:	microclimate volume
$\dot{V}O_2$:	oxygen consumption
$\dot{V}O_{2\text{-}N}$:	relative oxygen consumption per kg nude body mass
$\dot{V}O_{2\text{-}T}$:	relative oxygen consumption per kg total body mass
WC:	weight of clothing ensemble
WIC:	wetness in clothing
ΔCBM:	change in clothed body mass
ΔNBM:	change in nude body mass
3-D:	three-dimensional

CHAPTER 1 GENERAL INTRODUCTION

Chemical Protective Clothing and Challenges in Engineering

Chemical protective clothing (CPC) is designed to prevent damage to the body and fatalities from the effects of chemical and biological substances (Raheel, 1994). These substances can be in the form of solids, liquids and gases or any combination of these forms (Watkins, 1995). Due to the complexity of the hazard, CPC systems may vary greatly in their design, level of protection, and service time (Johnson, Henry, & Anderson, 1995). However, the mechanisms behind isolating humans from the hazardous environment mostly fall into two categories: provision of bulk and use of enclosure (Slater, 1996). In both cases, comfort and work efficiency may be compromised to achieve the desired protection. It is common to use an absorbent layer (provision of bulk) in CPC construction. This layer absorbs chemicals and biological agents before they reach the skin, thereby protecting the worker for a certain period of exposure. Work performance and mobility are highly impaired by the absorptive structure of CPC due to its bulky, thick, and heavy nature (Duncan, McLellan, & Dickson, 2011; Endrusick, Gonzalez, & Gonzalez, 2005; York & Grey, 1986). An impermeable barrier (use of enclosure) is another common method used in CPC engineering. Where this structure is present, air and water vapour cannot circulate between the body and the environment, which limits the heat dissipating mechanisms and leads to thermal discomfort and heat stress (Rossi, 2005; Slater, 1996).

Human Comfort and Work Performance in CPC

Comfort is a universal need that all humans constantly try to maintain and improve (Slater, 1985). The topic of comfort in protective clothing has been of interest to researchers for many years. It has been recognized that humans cannot perform their tasks efficiently if comfort is not maintained at a certain level (Bensel, 1997; Krueger & Banderet, 1997; Montain, Sawka, Cadarette, Quigley, & McKay, 1994; Slater, 1996). When considering comfort of CPC, aspects related to heat balance and freedom of movement are important factors to investigate. The main interests of this study are aspects of thermo-physiological and physical comfort. Definition and aspects of comfort are addressed in detail in Chapter 2.

When a thermal balance is achieved, an equal amount of energy is produced and lost by the body. Failure to maintain this thermal balance will eventually lead to reduced work efficiency and health risks (White & Ronk, 1984). The heat balance in CPC is often broken by the thermal insulation from the absorbent layers, the impermeability of the barrier material and the extra metabolic cost from the weight and burden of the protective clothing system (White & Ronk, 1984). Heat starts to store in the body and thermo-physiological strain occurs. Thick layers and rigid barrier materials used in CPC may also limit movement. As bulk and rigidity are increased, there is more likelihood that the bulky and rigid fabrics will interfere with the range and speed of joint motion. Physical burden in CPC during motions, therefore, is increased as protection is increased (Watkins, 1995).

The influences of CPC on comfort and work performance may be studied using a number of theories and test methods. Assessing a garment by wearing it is the most direct and realistic way. Most of the human-involved research has focused on specific CPC garment types and the effects they have on heat stress, comfort sensations, tolerance time, and worker acceptance under very specific circumstances (Coca et al., 2008; McLellan, 2008; Rissanen, Jousela, Jeong, & Rintamaki, 2008; Taylor & Orlansky, 1993; Veghte, 1989). Generally, CPC has been shown to add thermo-physiological strain and physical burden to the worker due to added thermal insulation, barrier system, weight, bulkiness and some garment design features (Barker & Scruggs, 1996; Coca et al., 2008; Dorman et al., 2006; Rissanen et al., 2008; Shalev et al., 1996). In addition, the environmental conditions, work rate and work/rest shifts have also been shown to influence the physiological responses (Rissanen et al., 2008; Veghte, 1989; White, Hodous, & Vercruyssen, 1991). Another method to predict the comfort provided by protective clothing is to study the physical textile and garment properties. Bench-scale laboratory tests on fabric thermal and mechanical properties are a practical alternative to expensive, time consuming wear trials (Barker, 2002; Cowan, Tilley, & Wiczynski, 1988; Frydrych, Sybilska, & Wajszczyk, 2009; Slater, 1986). Full-scale manikin tests, taking into account factors that are related to garment style, fit and body posture and motion, have become a very popular tool in comfort evaluation of protective clothing (Holmer, 2004; Wang, 2011).

Statement of Problem

The effects of protective clothing on workers' performance and comfort have been studied in a number of different situations. From the perspective of textile and clothing engineering, some researchers have focused on characterizing comfort-related fabric properties, such as thickness, air permeability, thermal insulation, and evaporative resistance (Frydrych et al., 2009; Kilinc-Balci, 2010; Sztandera, 2008; Zuo & McCullough, 2005). Others have emphasized aspects of the garment as a whole and evaluated overall garment comfort and performance using full-scale techniques such as three-dimensional scanning and manikin testing (Adams & Keyserling, 1995; Bendkowska, Klonowska, Kopias, & Bogdan, 2010; Celcr, Meinander, & Gersak, 2008; Lee, Hong, & Hong, 2007). Results from physical laboratory fabric and garment testing may be helpful in making comparisons between fabrics and garments. However, without systematic study and further validation, these objective results do not lead to accurate predictions of actual thermo-physiological strain and physical burden in CPC garments. In the area of occupational physiology, subjective evaluation and objective measurements of clothing comfort and work performance have been investigated with the involvement of human participants over extended time periods (Cortili, Mognoni, & Saibene, 1996; Dorman & Havenith, 2009; Headley, Hudgens, & Cunningham, 1997; Heled, Epstein, & Moran, 2004; McLellan, 2008). Nevertheless, it is difficult to generalize the findings from these studies to other settings since the conclusions were limited to the particular types of CPC and the specific conditions under which the investigations were conducted. Understanding the relationships between fabric and garment properties and the associated thermo-physiological strain and physical burden during work with CPC is still limited. There is a gap between the textile studies and the human response studies. A systematic and holistic approach is needed to serve as a bridge between the two perspectives and to offer a reasonable prediction of thermo-physiological strain and physical burden of CPC based on the material properties and/or garment parameters.

Dissertation Overview

Research purpose

The purpose of this research is to determine the comfort and strain in selected CPC through multi-level evaluation methods, to relate the characterized fabric and garment properties to the physiological responses from human wear trials and to develop regression models which predict the levels of thermo-physiological strain and physical burden of wearing CPC based on material/garment properties. This purpose was accomplished in four steps:

1. The material properties that relate to physical and thermal comfort were determined for different CPC materials to provide fundamental data for an evaluation of the thermo-physiological strain and physical burden of CPC made of these materials.

2. Garment characteristics, especially those related to ergonomic and thermal performance, were determined through advanced analyses of three-dimensional body scanning and thermal manikin testing. The full-scale results were then used to assess the thermo-physiological strain and physical burden of these CPC garments.

3. The thermo-physiological strain and physical burden in selected CPC systems were determined through controlled human wear trials.

4. The relationships between the results from the wear trials and the results from the fabric and garment testing were analyzed. Multiple regression models were developed to predict physiological strain and physical burden associated with wearing of CPC based on their material properties and/or garment measurements.

Chapter 2: Review of literature

Significant research in the fields of chemical protective clothing and the associated strain and discomfort in the last 40 years is reviewed in Chapter 2. This ranges from the history, construction and classification of CPC, the chemical resistance performance, strain and discomfort with wearing CPC, to factors affecting clothing comfort and different methods for clothing comfort evaluation. It is shown that most of the published research has been conducted on objective fabric/garment testing and on physiological responses and subjective comfort sensations through wear trials, but limited research has been conducted regarding comfort and performance prediction based on a thorough analysis of CPC properties and a systematic statistical approach.

Chapter 3: Comfort evaluation of CPC at fabric level

The dissertation begins with a series of bench-scale tests on the comfort related properties of CPC textile materials. The thermo-physiological strain and physical burden associated with the wearing of CPC are evaluated by analyzing the physical properties of the textile materials. These included fabric thermal properties (i.e., air permeability, thermal insulation and evaporative resistance) and mechanical properties (i.e., resistance to tensile, bending, shearing, compressional and surface frictional forces). A simple multi-axis model is proposed for the prediction of physical burden. Fabric thermal insulation and evaporative resistance are measured using a sweating guarded hot plate. The results are compared for the evaluation of thermo-physiological strain of CPC made of these materials.

Objectives

Objective 1 of this study was to:

-determine and characterize comfort-related physical and thermal properties of different CPC textile materials, these properties include:

a) fabric mechanical properties tested at low stress for resistance to:

(i) tensile;

(ii) bending;

(iii) shear;

(iv) compression; and

(v) surface friction.

b) heat and moisture transfer properties

(i) thermal and evaporative resistance

(ii) air permeability

Hypotheses

To meet the above *Objective 1*, the following null hypotheses were tested:

H_{o1} – There is no significant difference among CPC textile materials as regards their fabric mechanical properties, such as resistance of tensile, bending, shear, compression and surface fictional forces.

H_{o2} – There is no significant difference among CPC textile materials in heat and moisture transfer properties (i.e., thermal and evaporative resistance and air permeability).

Chapter 4: Comfort evaluation of CPC at garment level

The second study in this dissertation investigates the effect of clothing microclimate configuration on heat and moisture transfer through CPC garments. The assessment and prediction of clothing thermal comfort based on material properties did not take into account garment design and construction factors. These factors include, but are not limited to: covered body surface area, looseness or tightness of fit, garment openings, the adjustment of garment features, and the distribution of textile layers and air layers over the body surface (McCullough, 2005). Average air gap size, volume of microclimate, and heat and mass transfer properties of twelve different chemical protective (CP) coveralls (4 materials × 3 sizes) were investigated at the garment level. Physical burden and thermal strain in these coveralls were predicted using the data obtained from full-scale 3-D scanning and sweating manikin testing and compared with the results from bench-scale tests.

Objectives

Objective 2 of this study was to:

-use 3-D scanning to determine and analyse the differences in clothing microclimate volume, air-gap size/distribution between the clothing and the body among different CP coveralls and sizes.

Objective 3 of this study was to:

-determine the differences in thermal insulation and evaporative resistance of CP coveralls among different materials and sizes using a thermal sweating manikin.

Hypotheses

To meet *Objectives 2 and 3* of this study, the following null hypotheses were tested:

H_{o3} – There is no significant difference in air gap size and microclimate volume among different types of CPC and within CPC type when size changes.

H_{o4} – There is no significant difference in full-scale thermal insulation and evaporative resistance among different types of CPC and within CPC type when size changes.

Chapter 5: Comfort evaluation of CPC through human trials

Despite the efforts made in predicting clothing physical comfort and thermo-physiological comfort through fabric and garment testing, there are important characteristics of clothing comfort which only can be observed and evaluated by having living subjects wear the clothing (Choudhury, Majumdar, & Datta, 2011). Human trials account for all of the parameters and interactions within the clothing-human-environment system. Thus it has great advantages over fabric and garment testing. In the third study of this thesis, human participants performed a prolonged exercise protocol at moderate intensity in different CPC. Objective physiological measurements and subjective rating of mobility and comfort-related sensations were obtained through controlled exercise protocols.

Objectives

Objective 4 of this study was to:

-determine the differences in thermo-physiological strain among CP coveralls and the control garment system when worn by human participants.

Objective 5 of this study was to:

-determine the differences in physical burden among CPC coveralls and the control garment system when worn by human participants.

Hypotheses

To meet *Objectives 4 and 5* of this study, the following null hypotheses were tested:

H_{o5} – There are no significant differences in the thermo-physiological responses from human wear trials when different types of CP coveralls are worn.

H_{o6} – There are no significant differences in physical burden reported by test subjects when wearing different types of CP coveralls.

Chapter 6: The development of predictive models

Associations were determined between the physiological responses and subjective ratings from Chapter 5 and the material properties and garment ergonomic aspects obtained in Chapter 3 and 4 by Pearson's correlation tests. The dependent variables (physiological responses and subjective comfort perceptions) and independent variables were selected based on the strength of linear relationships and the rule of less intercorrelation between independent variables. Predictive regression models for thermo-physiological strain and physical burden from wearing CPC were developed.

Objectives

Objective 6 of this study was to:

-determine the relationships between CPC material/garment properties and the measurements taken during human trials.

Hypotheses

To meet *Objective 6* of this study, the following null hypotheses were tested:

H_{o7} – There are no relationships between the thermal properties of the CPC fabrics and the physiological strain determined in human trials.

H_{o8} – There are no relationships between the mechanical properties of the CPC fabrics and physical burden determined in human trials.

H_{o9} – There are no relationships between CPC garment parameters and physiological strain determined in human trials.

H_{o10} – There are no relationships between CPC garment parameters and physical burden determined in human trials.

Chapter 7: Conclusions

The final chapter summarizes the results of the four studies. The conclusions drawn from each study in response to the hypotheses given above are reviewed. Contributions of this research are also discussed. Finally recommendations for future research are made based on the results of these studies.

Limitations and Delimitations

- The fabric and garment samples selected for this research were limited to six CPC textile materials in Study 1, four CPC types in Study 2 and three CPC types in Study 3.
- The design of the CP garments tested in this research was limited to one-piece hooded coveralls. The protection level of these coveralls are categorized as ISO Type 3, 4 and 5 (International Organization for Standardization, 2007).
- The participants for wear trials were male and in the age range 18 to 40 years.
- The available exercise physiological lab for the wear trials is not a controlled environment. The temperature of the lab was measured and was consistently at 23°C ± 2.0°C. The relative humidity was variable from season to season, however the day-to-day variation during all the tests was 0 to 30%. The temperature and relative humidity of the lab during each test was recorded.
- Other limitations such as limitations of the testing apparatus and limitations caused by human biological variability are addressed in corresponding chapters.

Definitions

For the purpose of this research the applicable terms are defined as follows:

Air permeability: is "the rate of air flow passing perpendicularly through a known area under a prescribed pressure differential between the two surfaces of a material" (American Society for Testing and Materials, 1996, p. 236).

Average air gap size: is the average distance between the points on the surface of the nude manikin and the surface of the clothing determined in 3-D scanning.

Clothing ergonomics: is the study of the relationships between the human body and the clothing worn (Li, 2001).

Comfort: is "a pleasant state of physiological, psychological and physical harmony between a human being and the environment" (Slater, 1985).

Energy cost: is the amount of energy needed for a person to do certain work. It is related to the work intensity and it can be estimated using the oxygen consumed (McArdle, Katch, & Katch, 1996).

Evaporative resistance: is the resistance a material or a clothing ensemble to the flow of moisture vapour from a surface with a higher vapour pressure to an environment with a lower vapour pressure (American Society for Testing and Materials, 2009).

Microclimate volume: is the volume of the space between the surface of the nude manikin and the outer surface of the clothing.

Oxygen consumption: is the volume of oxygen consumed by the body as a rate per minute (McArdle et al., 1996).

Physical burden: is the energy cost of movement due to the weight, stiffness, bulkiness, restrictions, frictions and other physical loads of protective clothing. In this study, how physical burden affects movement is measured using human subjects.

Thermal insulation: is the resistance of a material or a clothing ensemble to dry heat transfer by way of conduction, convection and radiation (American Society for Testing and Materials, 2005).

Thermo-physiological strain: occurs when the body cannot dissipate excess heat. It may be due to high heat production or heat gain from the environment. It also could result from the prevented heat dissipation caused by the thick and impermeable nature of protective clothing systems (Holmer, 1995; Nunneley, 1989; White & Ronk, 1984).

Uncompensable heat stress: occurs when the evaporative heat loss required to maintain a thermal steady state exceeds the maximal evaporative capacity of the environment during exercise or even at rest. In uncompensable heat stress situations, the body constantly stores heat. “This results in body temperature continuing to increase until either exhaustion occurs or the severity of the set of environmental conditions decreases” (Cheung, McLellan, & Tenaglia, 2000).

Work performance: refers to whether a person is able to perform his/her task efficiently.

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CHAPTER 2 REVIEW OF LITERATURE

Chemical Protective Clothing (CPC)

A brief history of protection against chemical hazards

The use of protective clothing can be traced back to when people used animal hides and furs to protect themselves from harsh environments and variable weather conditions. Articles as far back as the 1950s provide evidence of the recognition of the hazards faced by farmers exposed to pesticides (Rucker, 1994). Starting in the early 1970s concerns over the carcinogenic nature of agricultural and industrial chemicals, such as pesticides and asbestos, were voiced (Johnson et al., 1995; Wolfe, 1973). In October 1989 the international symposium on protective clothing held by ASTM committee F-23 focused on the performance of CPC in chemical emergency response (Henry III, 1989). In addition to civilian circumstances, new chemical, biological and nuclear threats were found in military, first responders' and anti-terrorism activities (Truong & Wilusz, 2005). In summary, there are a wide range of hazardous chemical substances from which individuals need to be protected—from agricultural pesticides, industrial chemicals, infected body fluids to chemical/biological warfare agents. These may appear in the form of solids, liquids, or gases (Watkins, 1995). The need for effective protection from all of these hazards have led to the development of chemical protective clothing. Today we find CPC in a variety of designs, materials, and methods of construction, each having advantages and disadvantages for specific applications.

Classifications of CPC

Classification by barrier material

CPC systems must possess some level of barrier performance to limit exposure to hazardous substances (Barker, 2005). Some believe that the answer to protecting against chemical agents is to have a totally encapsulated garment that is constructed with barrier materials impermeable to any toxic substances (Slater 1996; Raheel, 1994). However, the issue of being over-protected and creating discomfort and strain prevents this type of protective assembly from being applied in all circumstances. In practice, a variety of CPC barrier materials, which offer different levels of protection, are used to construct CPC for work places with different levels of chemical threats.

Among these types, permeable and semipermeable materials permit the transport of water vapour and air. Convective flow of air allows evaporative cooling of the body to occur. These types of CPC may be worn for emergency or “splash” protection, to provide a more comfortable, “breathable” garment that protects the wearer from some hazards for limited exposure periods (Watkins, 1995). The maximal protection period depends on the capacity of the sorptive materials, the water-repellency of the fabric surface, and the nature of the exposure hazards.

Impermeable materials, on the other hand, block air and water vapour transport in both directions. Impermeable materials are generally in the form of films or sheets rather than being composed of yarns or fibres. Garment parts are joined by adhesives or heat-sealing techniques to avoid stitching holes (Watkins, 1995). Prolonged working in CPC made of impermeable materials may significantly increase the danger of heat stress to the wearer (Truong & Wilusz, 2005).

Selectively permeable materials block most hazards including vapours inward from outside while allowing evaporative moisture dissipation from the body through the barrier to the environment. Development of these materials aims to solve the dilemma of protection and comfort (Truong & Wilusz, 2005). Research into the effectiveness of this type of material is ongoing. Permeable, semi-permeable and impermeable barriers still remain the most commonly used materials for the construction of CPC.

Classification by design, performance and service life

The type of CPC needed to protect the body from hazardous substances depends upon the hazard and the activity. CPC may be classified into different categories in terms of the design, performance and service life (Stull, 2005).

Classification of CPC by its design usually reflects the body part that the clothing protects (Stull, 2005). For example, hoods, face shields, and goggles provide protection to the head, face and eyes; gloves to the hands; coats, jackets, pants, and coveralls to the body; and boots and shoes to the feet (Raheel, 1994).

This method of classification may also indicate specific design features that differentiate CPC items for the same body parts. For example, a one-piece coverall is differentiated from a two-piece (jacket and pants) design although they both are designated for protection of the torso, arms and legs.

Classification by performance makes it possible to indicate the actual level of protection and performance provided by the CPC. The performance is related to the types of protection offered against different forms of anticipated hazards, such as, liquids, vapours, particulates and combinations of the same. Standard tests are completed to demonstrate how well the CPC performs in terms of the desired protection. The classification of CPC by performance (e.g., particulate penetration-resistant, liquid penetration-resistant, vapour-resistant, permeation-resistant) then can be issued according to the test results. In addition to design and performance, CPC can also be classified by service life: durability (disposable, limited time use, and reusable), ease of restoration (capability for cleaning, decontaminating, and repairing) and life cycle cost (Stull, 2005).

Overall classification of CPC by standards developing organizations

An overall type classification of CPC can be made with respect to the combined consideration of design, performance, and service life. Some international, regional and local standards bodies have their own classifications of CPC, such as International Organization for Standardization (ISO), European Committee for Standardization (CEN), the American Occupational Safety and Health Administration (OSHA) and American National Fire Protection Association (NFPA). In Canada, Canadian Standards Association (CSA) is the national standards body. There is a standard, CAN/ CGSB/CSA-Z1610, published by CSA in 2011, which is related to the protection of first responders from chemical, biological, radiological, and nuclear (CBRN) events. However, standard specification and classifications of CPC are still under development (J. Batcheller, personal communication, February 19, 2014). Currently, CPC in the Canadian market are classified and tested to ISO or American standards.

In the United States, the Occupational Safety and Health Administration (OSHA) has developed a selection scheme for personal protective equipment for hazardous waste operations and emergency response based on level of protection and garment design. Their scheme consists of four levels designated by the letters

A, B, C, and D. Level A protection (highest level of protection) involves complete coverage with a totally encapsulating suit, a self-contained breathing apparatus (SCBA), chemically resistant gloves (double layer), boots, plus other safety equipment. Level B protection also requires the same breathing apparatus as level A, but a hooded chemical-resistant suit, gloves (double layer), chemically resistant boots, plus other safety equipment. Level C protection involves the use of an air purifying respirator and the same protective clothing as specified for level B, plus other safety equipment. Level D protection involves the use of coveralls with an option for gloves, boots, boot coverings, and other related safety equipment such as an air purifying respirator (Occupational Safety and Health Administration of the United States, 2014).

Similarly, NFPA 1991, 1992 and 1994 define CBRN ensembles as Class 1, 2, 3, and 4. Table 2.1 summarizes these different levels.

ISO 16602 – Protective clothing for protection against chemicals – classification, labeling and performance requirements establishes a 6-type classification system based on integrity, material chemical resistance and design. Type 1 refers to "gas-tight" chemical protective suit which covers the whole body, including hands, feet and head. A self-contained breathing apparatus or external source of breathable air is required for the Type 1 CPC system. Type 2 has the same clothing and breathing system as Type 1. The only difference is that Type 2 is "non-gas-tight". Type 3, "liquid-tight" CPC, consists of one-piece coverall or two-piece suit with or without hood or visor, with or without boot-socks. Type 4 is the same design as Type 3 with "spray-tight" performance. Type 5 is CPC providing protection against airborne solid chemicals, which could be a one-piece coverall or two-piece suit with or without hood and boot-socks. Type 6 is CPC consisting of a chemical protective coverall or two-piece suit with "limited protective performance against liquid chemicals". Table 2.2 gives the specific performance requirements of each type of CPC defined by ISO.

The overall classification of CPC may vary from one organization to another. OSHA designates CPC into 4 levels, A, B, C and D. NFPA also has four classes, 1 to 4, while ISO uses a six-type system, types 1 to 6. Despite the differences in the numbers of categories and the letters or numbers used, the similarity of these different classification systems is that they all are on the basis of the protection level determined in material level chemical resistance tests and/or whole garment integrity tests. In addition to chemical resistance performance, mechanical properties, thermal resistance, and comfort related properties of CPC are taken into consideration to assure the durability and performance in complex environments (Stull, 2005).

Chemical resistance performance and test methods

Chemical resistance is the principal basis on which CPC performance is based, thus it is the primary factor to consider in the selection of CPC (Raheel, 1994; Stull, 2005). Chemical resistance can be tested at the material level or garment level.

Material level chemical resistance tests

Material-level chemical resistance tests evaluate degradation, permeation and penetration. Typically, degradation is the obvious physical damage that occurs where a substance has contacted the CPC system (Stull, 2005). The degradation test, also known as chemical reactive test, is used to determine the effects of specific chemicals on materials. *ASTM D 471 Test Method for Rubber Property – Effect of Liquids* and *ASTM D 543 Practices for Evaluating the Resistance of Plastics to Chemical Reagents* establish standardized procedures for measuring specific physical properties of rubber and plastics before and after immersion in the selected liquids for a specified period of time under particular conditions. No criteria are given for determining acceptable performance since various chemicals can be used as the challenge. In practice, chemical degradation tests are used to evaluate the performance of gloves more often than garment materials (Stull, 2005). Overall degradation data may be used to rule out unsuitable candidate CPC materials, but is not used to recommend materials.

Penetration is defined as the bulk flow of a chemical through the physical spaces of the barrier material. Penetration may not be visible to the naked eye. It refers to the movement of matter through closures, porous materials, seams, pinholes or other imperfections in the protective clothing on a non-molecular level (American Society for Testing and Materials, 2003a). The test method for chemical penetration cited in NFPA standards is *ASTM F903 Standard Test Method for Resistance of Materials Used in Protective Clothing to Penetration by Liquids*. Penetration testing assesses the barrier performance of materials against liquid hazards.

Permeation is the diffusion of a chemical on a molecular basis through CPC materials. Raheel (1994) describes the process of permeation as having three steps: i. absorption of individual molecules of the chemical onto the exposed surface of the material; ii. molecular diffusion through the material matrix along a concentration gradient; and, iii. desorption of the chemical from the inside surface. A typical test for permeation is *ASTM F739 Standard Test Method for Permeation of Liquids and Gases through Protective Clothing Materials under Conditions of Continuous Contact* (American Society for Testing and Materials, 2012). Permeation testing detects chemical hazards at a molecular level; therefore it is the appropriate test when vapour or gas protection is required.

Garment level integrity performance tests

A material with good barrier characteristics against chemical penetration or permeation can be used to construct poorly designed clothing which can compromise the protection of the wearer. Thus, chemical resistance evaluations of garments are as important as evaluations of materials. Chemical resistance properties at the garment level or ensemble level are referred to as the overall CPC integrity performance. The garment parts being assessed in integrity performance include: seams, closures, interfaces with other clothing and equipment (such as sleeve ends to gloves, hoods to respirators, etc.). Common reasons for failure may include: lack of total encapsulation, material pinholes, incompletely closed zippers, defects in material seams and poor component interfaces. The integrity tests assess the ability of entire clothing system to prevent inward leakage of chemicals in the form of particulate, liquid and gas (Stull, 2005). Correspondingly, there are three principal types of overall product integrity testing: particulate-tight integrity, liquid-tight integrity and gas-tight integrity.

In a particulate-tight integrity test, the manikin or human subject is dressed in the test clothing system then exposed to a particulate atmosphere. A series of exercise activities may be performed by the subject. The particulate atmosphere and the atmosphere inside the CPC are tested on the contaminant concentration. The ratio of the concentrations indicates the level of resistance the CPC offers against the specific particle(s) (International Organization for Standardization, 2004a).

Liquid integrity tests determine if liquid enters to the interior of CPC. *ASTM F 1359 Standard Test Method for Liquid Penetration Resistance of Protective Clothing or Protective Ensembles Under a Shower Spray While on a Mannequin* involves placing clothing on a manikin and spraying the manikin with surfactant-treated water from five nozzles at a specified flow rate. A liquid-absorptive garment worn underneath the CPC is used for detecting liquid penetration. The test is qualitative and the criterion of pass/fail is whether or not liquid is detected inside CPC or on the inner absorptive garment (American Society for Testing and Materials, 2013).

Gas-tight integrity tests determine if gas or vapour can penetrate protective CPC. This test can only be applied to encapsulating, full-body suits with attached hand and foot protection. The most common approach for testing air-tight integrity, as described in *ASTM F 1052 Pressure Testing of Gas-tight Totally Encapsulating Chemical Protective Suits*, is to inflate the item to a specified pressure and then observe any change in pressure within the item after several minutes. A passing result requires that the suit maintain at least 80% of its inflation pressure over a 3-min period (American Society for Testing and Materials, 2009a).

Man-in-simulant test (MIST) is another standard test for garment integrity performance against vapour and involves human subjects and a series of physical activities. Human participants wear CPC along with a breathing apparatus and passive adsorption dosimeters (PADs). The PADs are affixed directly to the skin to determine how much vapour comes in contact with the body. The detailed protocols, procedures and requirements for this test method are specified in *ASTM F 2588*, including the locations of the PADs, activities, conditions of the controlled chamber etc. (American Society for Testing and Materials, 2007a).

Chemical resistance is the primary property of CPC. Results on chemical resistance not only state the protection level of the CPC system but also could be, to some extent, indicative of the comfort/discomfort level of this CPC suit. However, chemical resistance being summarized in this chapter as background knowledge is not the focus of this study and will not be further discussed in the following paragraphs.

Other tests related to overall performance of CPC

In addition to chemical resistance, the physical properties and human comfort related properties of a CPC system are also important in selecting the appropriate material for a particular application (Stull, 1987). Physical properties are tested to evaluate the weight, thickness, material strength, resistance to specific physical hazards (tearing, bursting, abrasion, cut, puncture, flammability, etc.), durability, and sensorial comfort. Thermal and evaporative properties are tested to evaluate the thermal and evaporative comfort of CPC (American Society for Testing and Materials, 2005a, 2005b, 2009b). Comfort, fit, and function can be evaluated qualitatively using human subjects (American Society for Testing and Materials, 1999). Some of these properties are used as criteria in the CPC classification (International Organization for Standardization, 2007; National Fire Protection Association, 2007). Since physical properties of CPC material and function/fit of CPC garments are closely related to wearing comfort, the relevant test methods and standards will be discussed in detail in the following chapters.

Strain and Discomfort Associated With Wearing of CPC

Definition of comfort/discomfort

With advances in textile technology, and an increasing need for high performance protective clothing, requirements for fabrics and clothing include not only protection and durability, but also comfort. Human beings cannot function satisfactorily if their comfort has been impaired beyond a certain level (Slater, 1996). However, comfort is such a subjective term that universal agreement on its meaning is almost impossible to achieve (Slater, 1985). Alternatively, people find it relative easy to define and describe discomfort. For example, Smith (1993) describes comfort as a neutral sensation, a freedom from pain, and ultimately, the wearer being unaware of the clothing that is worn. Whereas, Sontag (1986) gives a general definition of comfort as a mental state of well-being, or a state of equilibrium that exists between a person and the environment. Slater (1985) defined comfort as “a pleasant state of physiological, psychological and physical harmony between a human being and the environment”. This definition is useful as it separates the construct into distinct types of comfort: physiological, physical and psychological (Slater, 1985). Physiological comfort relates to the human body’s ability to continue functioning. Physical comfort is correlated with the effect of the external environment on the body. Psychological comfort is related to the ability to keep the wearer satisfied. When these comfort aspects are discussed in the context of CPC, CPC may negatively affect wearer's comfort in terms of heat stress or thermo-physiological discomfort. CPC may affect wearer's physical comfort by reducing work efficiency and limiting the movement and range-of-motion. Also the effects of CPC on aesthetic aspects and preference could cause the wearer to reject or misuse the clothing, which would leave the wearer unprotected from hazardous sources. In this research, an adaptation of Slater's (1985) definition of comfort and its three aspects is used.

Thermo-physiological strain

Human beings are homoeothermic—that is, their body temperatures remain relatively constant at 37ºC by constant energy exchange with the environment. Clothing acts to moderate this exchange (Fourt & Hollies, 1970a). When heat transfer into the body and heat generation within the body are balanced by heat output from the body, this is known as thermal equilibrium (Parsons, 1993). If heat generation and input are greater than heat output, the body starts storing energy. Heat is generated by metabolism as a result of the biochemical reactions of the human body. Environmental heat load is also a factor to consider when the ambient temperature is higher than body temperature (White & Ronk, 1984). In order to maintain thermal equilibrium, metabolic heat must be dissipated by evaporation (E), radiation (R), convection (C) and conduction (K). The heat balance equation is described as:

$$S = M \pm E \pm R \pm C \pm K \qquad \text{eq. 2.1}$$

Where,

S = rate of storage or loss of body heat (+ means the body is gaining or storing heat, - means heat is being lost)

M = metabolic heat production (always +)

E = evaporative heat exchange (usually -)

R = radiant heat exchange (may be + or -)

C = convective heat exchange (may be + or -)

K = conductive heat exchange (may be + or -)

(Fourt & Hollies, 1970a)

Conductive heat transfer occurs through the transfer of heat from objects directly in contact with one another. Convection refers to the heat transfer occurring by the movement of air or water over the surface of the body. Radiation refers to heat transfer in the form of electromagnetic rays. Under normal, resting conditions most of our body heat is lost through these three mechanisms. Heat lost by vaporization (or the forming of water vapour) from the skin and respiratory tract is called evaporation. The major avenue of evaporative heat loss is through sweating (Saville, 1999).

Conductive heat exchange is generally considered minimal and can be disregarded in the context of heat loss from the human body. At rest and in a neutral environment, convection is responsible for 10-15% of the heat loss, radiation, 60% and evaporation, 20-30% (White & Ronk, 1984). In a warm environment, evaporative heat loss plays a much more dominant role and the convective and radiative heat exchanges decrease.

Physiological strain associated with wearing protective clothing has been well recognized. Wearing protective clothing significantly increases metabolic rate during different exercise intensities and under various environments (Dorman & Havenith, 2009; Levine et al., 2001; Selkirk & McLellan, 2004). In the cases where impermeable barriers are used, CPC ensembles restrict evaporative heat transfer, and consequently the heat loss required to maintain a thermal steady state cannot take place. This is especially true when a person is working intensively or in a hot environment, creating a condition of uncompensable heat stress (the evaporative heat loss required to maintain a thermal steady state exceeds the maximal evaporative capacity through the CPC system) (Cheung, McLellan, & Tenaglia, 2000). In addition, liquid sweat starts to appear when the micro-environment (e.g., air layer between the garment and the body) reaches saturation. The presence of liquid sweat will cause a sensation of discomfort and therefore, reduce the work efficiency of the personnel wearing the garment. The body responds to heat stress by increasing heart rate, respiration rate, blood pressure and body temperature. All these responses lead to a diminished performance and increased fatigue or exhaustion for the wearer (Cheung, & Sleivert, 2004). In this study, the term "thermo-physiological comfort" refers to aspects of the CPC system which prevent evaporative heat loss (heat and moisture transport through CPC system) and contribute to heat stress.

Physical burden

CPC impair the wearer's comfort by introducing not only thermal stresses caused by their thickness and encapsulation, but also physical burdens due to the weight, bulkiness, stiffness, inflexibility, friction between fabric layers and restrictions from improper size, fit and poor design (Adams & Keyserling, 1995; Daanen, Reffeltrath, & Koerhuis, 2006; Rissanen et al., 2008; Tremblay-Lutter & Weihrer, 1996). It was found in many studies that wearing protective clothing significantly increases metabolic rate (Dorman & Havenith, 2009; Duggan, 1988; Teitelbaum & Goldman, 1972). As with any machine, the human "engine" is not 100% efficient. In fact, human work is typically about 25% efficient, that is, 25% of the energy consumed transfers into useful work. This amount is variable from person to person depending on the gender, age, body composition and fitness level. The work efficiency also depends on how familiar the person is with the tasks and the efficiency, load and restrictions of the tools and gears the person is working with (McArdle et al., 1996).

For a person wearing protective clothing, a good portion of all work done is against the weight of the clothing ensemble especially for tasks against gravity, such as stepping, climbing, getting up from knees etc. In an investigation on the effects of protective clothing on energy cost, Dorman and Havenith (2009) found that wearing a range of protective clothing caused an increase in energy consumption of 1% to 2.7% per kg of clothing weight. CPC ensembles, including garment, footwear, breathing apparatus and other accessories, may weigh up to 10-15 kg. The energy consumption of the wearer may increase significantly due to the weight of the CPC ensemble. In other words, in comparison to people who are not wearing the CPC ensembles, it costs more energy for this person to perform the same tasks. When prolonged moderate work load is performed, the person wearing CPC will reach fatigue sooner. When working at high intensity, more heat will be generated by the wearer of heavier CPC, resulting in a more severe negative impact on the heat balance of the body. Minimizing additional weight of protective garments in order to maintain normal human performance is a well-recognized principle of garment design and construction (Bishop, Ray, & Reneau, 1995; Raheel, 1994; Taylor & Orlansky, 1993; York & Grey, 1986).

Reduced mobility is seen in most cases where CPC are worn and is caused by garment bulk, stiffness, inability to stretch, poor fit and friction between fabric layers. Garment bulk resulting from thickness or extra ease at arms and legs may greatly interfere with movement. The chemical barrier materials used in CPC may also be rigid and further limit movement. When work must be accomplished by straining clothing through compression, bending, stretching, and shearing actions or by sliding one fabric against another, energy that could be used to accomplish a task is wasted (Watkins, 1995). In addition to mechanical properties of the fabric, the ergonomic aspects of the clothing are equally important in contributing to mobility of the clothing. These ergonomic aspects refer to the relationship between the dimensions of the garments and the human body, including size, fit and design features. The CPC with improper size, fit and poor design tend to have more physical burden on the wearer (Adams & Keyserling, 1995; Ashdown, 2011; Huck, Maganga, & Kim, 1997).

Impaired sensorial and psychological comfort

Sensorial comfort is the sensations of how the garment fabric feels when it is touched by hands and worn next to the skin. These sensations are often expressed as feelings of softness, smoothness, dampness, clinginess, prickliness, and the like (Barker, 2002). Sensorial comfort can also be related to the thermo-physiological comfort, as a fabric wetted through with sweat will change its properties and may, for instance, cling to the skin (Rossi, 2005; Saville, 1999). The tactile quality of fabrics is a key parameter in successful marketing strategies for conventional textiles. However, since CPC is seldom worn next to the skin, the tactile sensations of the materials used in their construction are considered less important than other properties, particularly those that influence their level of protection.

Psychological comfort deals with aesthetics (garment colour, construction, style, etc.) and the suitability of the clothing for the occasion/activity (Barker, 2002). CPC are limited in design, style, colour and even in size; therefore, psychological comfort is not usually considered in the manufacture of CPC.

However, psychological effects on the wearer may be important, particularly if the wearer feels inadequately protected in the garment.

The appeal to aesthetical aspects and sensorial feelings of CPC has been overtaken by the fundamental demands on protection and improvement of thermal/physical strains.

Factors Affecting Comfort and Comfort Evaluation

Clothing is an integral part of human life as an extension of human skin. It is important to realize that clothing is not just a passive cover over the body, but that it interacts with the body and the environment constantly (Fourt & Hollies, 1970a). It is isolative to discuss the comfort of clothing without putting it into the context of human and environmental parameters. Human comfort in a human-clothing-environment system therefore is determined by factors from three aspects: person attributes, clothing attributes and environmental attributes, as listed in Table 2.3 (Branson & Sweeney, 1991).

Clothing comfort can be evaluated or predicted using various subjective and objective methods. As shown in Figure 2.1, in his five-level system of physiological evaluation of clothing, Umbach (1983) indicated the best way to provide a realistic and comprehensive evaluation of the performance of clothing is through field tests. However these tests are unrealistic to test a variety of clothing systems because they are costly and it is difficult to control variables to get accurate and repeatable data. When the tests are used for extreme conditions, the difficulty of these problems becomes more serious, since a wide-range of environmental conditions cannot be tested with a human subject for safety reasons. Therefore it is important to develop some tests that can be performed in a laboratory or controlled environment.

Laboratory tests of textile properties are used to predict clothing comfort. For example, fabric weight, thickness, air permeability, thermal resistance, moisture and vapour permeability have been tested to relate fabric properties to human comfort sensations (Holmer, 1988; Lee & Obendorf, 2007; Slater, 1986; Zuo & McCullough, 2005). Small scale laboratory tests are a practical alternative to expensive, time consuming wear trials. Laboratory measures of textiles are convenient for comparing different fabrics, however, they do not take into account factors that are also related to garment fit and design. Data from physical laboratory test results are limited in use to making comparisons among fabrics. For example, elongation test can be performed to choose the most flexible fabric from a few candidate fabrics. The overall flexibility and freedom to motion of the finished garment is also dependent on the design, fit and ease of garment. Results from one small scale test do not lend themselves to broad generalizations or predictions of actual perceived comfort sensations of a garment.

Full scale thermal manikin tests take into consideration not only fabric properties but garment features on the three dimensional human form. Results from manikin tests are expected to better represent actual thermal stress than those from fabric testing. Several newly developed manikins can simulate human sweating and provide valuable information about heat exchange by evaporation (Fan & Qian, 2004; McCullough, 2005; Tamura, 2006). Some even consider the effects of human movements and can be operated with walking or cycling simulation (Holmer, Gavhed, Grahn, & Nilsson, 1992; Kuklane, 2008). Manikin testing is more complex, difficult to control, time consuming and expensive in comparison with fabric testing. However, for the same exposure conditions, thermal manikins measure heat and moisture transfer in a more relevant, realistic way than fabric testing while being quicker, more reliable and accurate than human trials.

The advantage of human trials, on the other hand, is that they take into account complex combination of environmental conditions, garment design and the interactions among the environment-clothing-human system. Wear trials can relate the results directly to the clothing in actual use but tend to be inconsistent and costly and can sometimes expose the subjects to danger when testing under extreme conditions. For these reasons, physiological strains and perceived comfort ratings from human wear trials are often correlated with small scale laboratory tests and/or manikin tests (Holmer, 1988; Konarska, Soltynski, Sudol-Szopinska, & Chojnacka, 2007; O'Brien et al., 2011).

Material Evaluation of CPC Comfort

Textile properties related to comfort

Thickness and mass

Thickness and mass of fabrics usually change in proportion to each other and may be discussed together. According to Fourier's law of heat conduction, the insulation of a material is generally proportional to its thickness. Fabric is a mixture of fibres and trapped air layers. The thermal insulation of a fabric is determined by the properties of fibre materials and fabric construction, the layers of trapped air in the fabric and the air layers between fabrics layers (Holmer, 1988). The thicker the fabric, the more air trapped in the fabric structure, and the higher the thermal insulation. It is found that variations in fabric mass without major changes in thickness will not significantly affect the thermal insulation of a fabric (McCullough, Jones, & Zbikowski, 1983). Thickness and mass also add an extra load for the wearer to carry around and tend to increase fatigue and thus reduce physical comfort.

It is commonly seen in clothing comfort studies that thickness and mass were included as fundamental fabric characteristics for the purpose of differentiating among fabrics (Frydrych et al., 2009; Lee & Obendorf, 2007; Rego, Verdu, Nieto, & Blanes, 2010; Rombaldoni, Demichelis, & Mazzuchetti, 2010). In other studies, thickness and mass were controlled so that the effects of other attributes, such as: fibre composition, fabric structure, air permeability etc., on fabric comfort could be determined (Yoo & Barker, 2005). Thickness and mass can also be used directly as indicators in comfort prediction (Cowan et al., 1988; Verdu, Rego, Nieto, & Blanes, 2009). It is a well-accepted principle to keep the fabric as thin and light as possible, providing that the requirements for protection and function for the specific application are met.

Mechanical and surface properties

Physical comfort of wearing a garment is essentially a result of how much physical stress is generated in the fabric during wear and how the stress is distributed over the skin and to the muscles (Slater, 1985; Watkins, 1995). For example, when an individual is walking, the physical burden he/she encounters includes the weight of the fabric, friction between garment surfaces, and physical strains caused during stretching, bending, and shearing of the fabric. The heavier, the rougher, and the stiffer the fabric is, the greater the physical burden. Therefore, the physical comfort associated with wearing CPC has a strong relationship to the mechanical and surface properties of the fabric. These properties include tensile, shearing, bending, compression, friction, surface roughness etc. Previous research has documented the relationships of these properties to comfort (Barker & Scruggs, 1996; Cardello, Winterhalter, & Schutz, 2003; Cowan et al., 1988; Kirk & Ibrahim, 1966; Rombaldoni et al., 2010; Verdu et al., 2009). Kirk and Ibrahim (1966) also found that increased extensibility gave greater wear comfort to conventional clothing.

Several researchers have used the Kawabata evaluation system (KES) as a tool to predict fabric hand and sensorial comfort perceptions by rapidly measuring fabric mechanical and surface properties at low stresses (Barker & Scruggs, 1996; Cardello et al., 2003; Cowan et al., 1988; Rombaldoni et al., 2010; Verdu et al., 2009; Yoo & Barker, 2005). In the protective clothing research area, KES has been used for the sensorial comfort evaluation of chemical splash resistant fabrics (Cowan et al., 1988) and for nuclear protective clothing fabrics (Barker & Scruggs, 1996). In both studies, subjective comfort sensations, such as, hand, smoothness, stiffness, stretchiness, and heaviness were also evaluated subjectively during wear trials. Cowan et al. (1988) found correlations between subjective rankings of fabric stiffness and smoothness and the corresponding KES objective evaluations.

Kawabata evaluation system

The Kawabata Evaluation System (KES) was developed by the Japanese scientist Kawabata and his coworkers in 1970. This system measures with high sensitivity the mechanical properties of fabrics at low stresses, simulating the forces typically encountered when a fabric is handled or manipulated by hand. Mechanical properties, including resistance to tensile, shearing, bending, and compressional forces, as well as surface roughness are tested (Jeguirim et al., 2010), Figure 2.2 and Table 2.4 show the parameters that can be obtained from the KES.

The KES is used widely for testing fabric stiffness, thickness, extensibility, surface smoothness, and bulkiness (Avinc, Wilding, Gong, & Farrington, 2010; Jeguirim et al., 2010; Lam, Kan, Yuen, & Au, 2011; Liu, Kwok, Li, & Lao, 2010).

It also provides “total hand” values (i.e., the degree of “good” hand). According to Kawabata (1980), “good hand is an evaluation of the primary quality of fabrics, the quality is concerned with comfortability and beautiful appearance” as well as in “conformity with function of garment and with human sense” and evaluates fabrics for specific end uses according to the recommended values (Radhakrishnaiah, Tejatanalert, & Sawhney, 1993). In this thesis, the KES was used to determine the tensile, shearing, bending, compression, surface friction, and roughness properties of the CPC fabrics. Tactile sensations and the physical burden of the fabrics were predicted and compared through an analysis of the individual attributes measured by KES.

Heat and moisture transfer properties

Many researchers agree that a dominant factor contributing to thermo-physiological comfort is the movement of heat and moisture though a garment system (McCullough, Huang, & Kin, 2005). Ideally, CPC should provide adequate protection against chemical hazards, allow heat dissipation to the environment, and move moisture away from the body without feeling wet. Dissipation of heat and evaporation of moisture from a clothed body depends on the following factors: wearer’s activity level, ambient temperature, environmental humidity, external air movement, and fabric properties related to heat and moisture transfer (i.e., fabric thickness, enclosed air space, fabric structure and fibre content) (Slater, 1986). From the perspective of textile science and engineering, regardless of the influences of human and environmental factors, clothing that has a low thermal insulation and high water vapour permeation resistance will allow the heat absorbed from the sun or other radiation sources and the heat generated by the body to dissipate more efficiently through heat and moisture transfer (Gibson, 1993; Holmer, 1988; Rego et al., 2010). The transfer of heat and moisture through a textile material is a complex process that is affected by many interrelated material characteristics; however, there are available techniques for measuring thermal and evaporative resistance of textile materials.

Sweating guarded hot plate

One of the most widely used and best standardized test methods for heat and moisture transfer is the sweating guarded hot plate (Rossi, 2005). The sweating guarded hot plate, also called the “skin model,” tests thermal and evaporative heat transfer properties of a fabric system and the air layer above it.

The skin model consists of an electrically heated plate, which is located in a climatic chamber. The plate is heated to 35 °C and the measuring surface is surrounded by a guard that is heated to the same temperature to avoid any heat loss from any direction other than the measuring surface. Fabric samples are put onto the plate, with ambient conditions at desired levels.

The thermal resistance (R_{ct}, m^2K/W) is assessed from the supplied steady-state heating power (Q), the temperature difference between the ambient (T_a) and the skin model (T_s) and the size of the measuring surface (A):

$$R_{ct} = A\,(T_s - T_a)/Q \qquad \text{eq. 2.2}$$

(American Society for Testing and Materials, 2009b)

The resistance to dry heat transfer (R_{ct}) obtained from a dry test reflects the heat transfer properties of the whole fabric system; that is, the combined effects of conduction, convection, and radiation of heat from the hot plate surface through the material to the environment (Rossi, 2005).

In the wet test, water is supplied to the test plate to simulate sweating. The plate is covered by a cellophane foil permeable only to water vapour to prevent a contact of the sample with water on the plate. The heating power required to compensate for evaporative cooling while maintaining the plate at 35 °C is proportional to the water vapour permeability of the material being tested. The evaporative resistance (R_{et}, m^2Pa/W) is determined by the supplied steady-state heating power (Q), the water vapour partial pressure difference between the ambient air (p_a) and the skin model (p_s) and the size of the measuring surface (A):

$$R_{et} = A\,(p_s - p_a)/Q \qquad \text{eq. 2.3}$$

(American Society for Testing and Materials, 2009b)

R_{et} is related to the flow of moisture from the saturated hot plate surface through the material to the environment (Rossi, 2005).

Sweating guarded hot plate has been widely used to evaluate thermal comfort performance of clothing for sports, cold weather, thermal and nuclear protection (Barker & Scruggs, 1996; Holmer, Nilsson, & Meinander, 1996;

McCullough et al., 2005; Prahsarn, Barker, & Gupta, 2005; Yoo, Hu, & Kim, 2000). Different standard test methods have been developed for measuring the dry thermal resistance and the evaporative resistance of fabrics using a hot plate apparatus. These methods include: ASTM D 1518, ASTM F 1868, and ISO 11092. Interlaboratory studies have been carried out to validate the accuracy and reproducibility of sweating hot plate (McCullough, Huang, & Kim, 2004). It is the most widely accepted fabric level test method for the evaluation of thermal comfort.

Air permeability

Air penetration has an impact on clothing thermal insulation by inducing air (temperature and humidity) exchange. Depending on the construction of a fabric and clothing style, air may be forced through the pores in the fabric as well as through the openings of the garment. The air permeability of a fabric is a measure of how well it allows air to pass through it. CPC materials have very low air permeability or are totally air impermeable (Truong & Wilusz, 2005). In totally impermeable materials, air flow through clothing layers is not possible, thus moisture vapour can only move out of the clothing system through vapour diffusion. However, if the fabric is air-permeable and there is a pressure gradient across the fabric, air flow through the fabric (convection) will take place and will have an impact on vapour diffusion. Air flow can be in the same or the opposite direction to vapour diffusion; correspondingly, convection may oppose or aid vapour diffusion flux (Gibson, 1993).

Dynamic moisture permeation cell

The dynamic moisture permeation cell (DMPC) was developed by Phil Gibson in 1997 (Gibson, Kendrick, Rivin, & Charmchi, 1997). This method measures water vapour diffusion resistance and air permeability (resistance to air flow) in the same test. In this test, the pressure drop across the sample is systematically changed to produce different air flows through the fabric (McCullough, Kwon, & Shim, 2003). Since there is a humidity difference across the sample, the water vapour diffusion property can also be determined from this test. At zero pressure drop, the true water vapour diffusion resistance property and the true water vapour transmission rate are verified (American Society for Testing and Materials, 2003b; Gibson et al., 1997) as shown in Figure 2.3 CPC materials are designed to offer different levels of protection and to serve in various environments. The DMPC can be used to simulate different environmental conditions such as hot or cold, dry or humid, windy or mild, high or low humidity. The DMPC can also indicate the effect of air flow on water diffusion. Moreover, the DMPC test can be performed much faster and requires a much smaller specimen size than the sweating hot plate test. Therefore, the DMPC is a very useful and efficient test for evaluating the thermal comfort of CPC, especially in cases where evaporative heat transfer is the main concern.

Other textile properties

The wickability of fabric is important to liquid sweat dissipating because liquid water can be transported to the external environment through fabric by wicking, or capillary action (Li, 2001). The liquid sweat can be wicked along the outside of fibers and through the interstices in the fabric. A high wickability can draw water away from the skin surface as soon as possible and keep it dry. The ability of a fabric to do this is dependent on the surface properties of the constituent fibres and their total surface area, which are governed by factors such as the fibre size, the yarn structure and the fabric structure (Slater, 1986). The capillary network of the fabric is dependent on the direction under consideration so that the wicking properties through the thickness of the fabric may be different from those in the plane of the fabric (Fourt & Hollies, 1970b). For clothing worn right next to skin, the water absorbing behavior, water holding capacity and drying time are also very important to the feeling of damp or wet. Since CPC are usually worn on top of some undergarments, these properties will not be considered in this research.

Full Garment Laboratory Evaluation of CPC Comfort

The thermo-physiological strain and physical burden associated with wearing of CPC can be evaluated by analyzing the physical properties of the textile materials. However, the assessment based on material properties does not take into account garment design and construction factors. These factors include: covered body surface area, garment fit (looseness or tightness), garment openings, the adjustment of garment features, and distribution of textile layers and air layers over the body surface (McCullough, 2005).

It is obvious that garments (e.g., vest vs. coverall) made from the same material can provide different overall thermal insulation and evaporative resistance due to differences in the surface area of the body covered by the garment (Lee et al., 2007). The garment that covers the greater surface area provides greater overall thermal and evaporative resistance. Chemical protective clothing typically covers all parts of the body (encapsulates) and therefore increases thermal and evaporative resistance over other types of garments. Garment opening and closure features also have an impact on thermal and evaporative resistance especially during movement. This is because different features (e.g., elastic cuff vs. flat cuff; zipper closure vs. zipper and Velcro closure) may influence the ventilation through the garment (Stull, 2005). CP garments have closures to prevent ventilation or influx of air and these closure systems contribute to thermal and evaporative resistance. Garment fit and resultant air volume in the microclimate is a critical factor for determining the thermal insulation value of a clothing ensemble (McCullough & Hong, 1994). A relatively loose fit enables a wider range of motion and better ventilation (Daanen et al., 2006). Garment weight, alone or confounded with other product variables, is clearly a burden associated with wearing of protective clothing (Dorman et al., 2006)

Garment ergonomics and its effects on comfort

Clothing ergonomics is the study of the relationships between the human body and the clothing worn. It encompasses several identifiable but interdependent variables: the shape and dimensions of the wearer and the clothing, the relationships between the two systems, the weight of the clothing, body movement and any changes to this which result from wearing the clothing (Li, 2001). Clothing ergonomic analysis is important to all types of clothing in terms of sizing and obtaining best fit, however, it becomes extremely critical with protective clothing systems which are expected to provide protection without restricting task performance.

Garment fit

The investigation of how well a garment fits a person includes i. the shape and dimensions of the wearer; ii. the shape and dimensions of the clothing; and iii. the relationship between the two systems (Li, 2001). Fit can be evaluated as static fit or dynamic fit. Static fit is defined as the relationship between garment size and body size. Dynamic fit looks into whether a garment allows the body to perform usual tasks without garment interference and resistance. Static fit can be tested using live models and body forms (Pechoux & Ghosh, 2002). Fit testing using live models is subjective, qualitative and time consuming. The general procedures include selection of participants, collection of basic information and dimensions of the participants, definition of perception of fit, a relative long wearing period, recording and analyzing the response of wearers on perceptions of fit etc. (Pechoux & Ghosh, 2002). Fit testing can also be done using flat or volumetric body forms. These forms were constructed in different sizes based on combinations of height and weight. Body forms are objective and were widely used in garment sizing by providing “ideal dimension models to set up a valid sample population” (Pechoux & Ghosh, 2002, page 31). However, body forms have the disadvantages of being static and part of the objectivity is lost when assessors make their subjective judgment on the level of fit.

Although dynamic fit is most relevant to the effects of clothing on human comfort and performance, static fit provides the basic information of body dimensions, clothing dimensions and resultant ease, which allows clothing geometry to be assessed in relation to comfort and performance (Pechoux & Ghosh, 2002).

Effect of fit on thermo-physiological strain

Garment fit and resultant air volume is critical in both heat and mass transfer processes (Berger & Sari, 2000). Air layers with different sizes contribute differently to thermal insulation due to the presence/absence of convective heat loss (Lee et al., 2007; Song, Ding, Wen, & Gonzalez, 2007). Chen et al. (2004) conducted a study on a thermal sweating manikin. Five sizes: S, M, L, XL and XXL were tested. Their results showed that, the thermal insulation increases with the thickness of the air gap when the air gap was small. The rate of increase gradually decreased as the air gap became larger. When the air gap exceeded 10 mm, the thermal insulation decreased. The larger air gap was thought to allow heat loss through natural convection. The results from this work agreed with the conclusions made by Lotens and Havenith (1991), who reported in their study that the maximum thickness of a still air layer is usually estimated at 12 mm.

The effect of air layers on evaporative resistance is even more complex (Song et al., 2007; Wen, Song, Kainat, & Adeeb, 2012), especially when the interactions with material structure and permeability are taken into consideration.

For impermeable CPC, the total air volume in the micro-climate is expected to be a critical factor in determining the tolerance time for a person since water vapour keeps accumulating until saturation is reached in the micro-climate. The air gaps in permeable CPC, to some extent, slow down the process of evaporation from the body by the surrounding air flow, therefore, increasing the air gap size is expected to cause an increase in evaporative resistance (Lee et al., 2007). Yoo, Hu and Kim (2000) investigated the effects of air layer thickness on vapour pressure changes in the microclimate. They controlled the air layer at 6, 12 and 18 mm, and found that for both cotton and PET fabrics, when the thickness of the air layer doubled from 6 to 12 mm, the vapor pressure decreased significantly. However, if the thickness of the air layer continues to increase up to 18mm, the density of water vapour in the air layer decreases relatively more slowly and the driving force for water vapour to go into the ambient air decreases (Yoo et al., 2000). It was therefore believed that there is an effective air layer thickness for wearing comfort. Yoo, Hu and Kim’s model, to some extent, explains how a certain thickness of air layer is preferable in terms of moisture comfort.

Effect of fit on physical burden

In addition to its effects on thermo-physiological strain, fit also has an impact on the physical aspect of wear comfort. Even when garments are custom fitted (statically), most body dimensions are obtained on persons in the standing position. The way a garment feels can vary with movement (standing, sitting, kneeling, walking, bending, etc.) and wearing period (Pechoux & Ghosh, 2002). Dynamic fit, therefore, can only be evaluated by human subjects. Range-of-Motion (ROM) and/or restrictions to wear mobility are commonly used parameters in the evaluation of dynamic fit. Restriction to wearer mobility was investigated in Huck’s (1988) study on three different protective clothing types. The Leighton Flexometer and a simple protocol were used to quantify the loss of body movement attributable to wearing protective clothing and equipment. Adam and Keyserling (1995) investigated the effects of garment size on ROM. Three size levels (undersized, appropriately sized and oversized) were studied. The ANOVA test results showed that garment size significantly affected ROM, but ROM also may be affected by other garment parameters which are interdependent with garment size, such as garment style, fabric stretch, stiffness, bulk, etc. A relatively loose fit enables a wider movement range before the size becomes so large that the bulkiness becomes a physical hindrance to movements.

As discussed above, ergonomic analysis of clothing fit and air gap size and distribution is critical for protective clothing systems since it has an impact on both physical and thermo-physiological comfort. Traditional one- or two-dimensional measurements of body size and garment size provide only limited information of the fit at selected locations, and do not reflect the actual position of a garment when worn, therefore the overall effects from the full-scale garment cannot be investigated thoroughly (Dorman et al., 2006; Huck et al., 1997). A more informative and comprehensive approach to determining clothing ergonomic factors is needed.

New techniques used to determine garment ergonomics

Three-dimensional scanning for fit and ease evaluation

A 3-D body scanner is a non-contact optical measuring system capable of rapidly generating a 360° representation of the surface geometry of an object. Whole body scanners consist of:

- one or more light sources that project a line or other pattern on an object;
- cameras that capture the image of the projected light on an object;
- software to extract the depth structure of the surface of an object; and
- a computer screen to visualize the 3-D surface.

(Daanen & van de Water, 1998)

For a body scanner that uses laser scanning, a horizontal line of light is projected onto the object and reflected back into cameras located in a series of scan heads. The cameras move vertically along the length of the scanning volume, illuminating the object via an arrangement of mirrors. The displacement of the light pattern is then used to calculate the distance from the subject to the camera, from which software then inverts the distance data to produce a 3-D representation depicted as a cloud of data points. The result is an accurate, 3-D replica of the object.

Whole body scanners have applications in diverse areas of research and industry. For apparel industries, this technology has been used to improve the sizing of garments, particularly for segments of the population that have not been represented in the target markets by ready-to-wear manufacturers (Ashdown &

Dunne, 2006). Anthropometric research requiring large-scale sizing surveys, such as for the military, also benefit from 3-D body scanning. 3-D scanning also has relevance for medical fields, industries that require body shape analysis, such as for health and fitness. 3-D scanning also has use in the design and evaluation of ergonomic prototypes and products (e.g., airline, automotive, and furniture industries) (Daanen & van de Water, 1998).

In recent years, studies have been conducted using 3D body scanning to measure, quantify, characterize and investigate aspects of garment ergonomics such as fit, ease, air gap and/or air volume of garment systems (Lee et al., 2007; Mah & Song, 2010a; Psikuta, Frackiewicz-Kaczmarek, Frydrych, & Rossi, 2012). In Lee, Hong & Hong's (2007) research, 3-D quantification of air volume was accomplished by the adoption of non-contact image scanning technology, phase-shifting moiré topography. They were able to show the distribution and total amount of air volume within the clothing microclimate and use it to predict clothing local and overall insulations. The results from thermal manikin tests showed that the thermal insulation of the clothing system increased as the air volume increased. However, it was also observed that when the air volume exceeded 7×10^3 cm^3, a convective cooling effect took place (Lee et al., 2007). The influence of air gap size in coveralls on thermal protection from flash fire hazards was investigated by Mah and Song (2010b). A measurement protocol using 3-D scanning was developed to determine the size of the air gaps at sensor locations and the distribution of these air gaps over a female mannequin. In general, areas of the female mannequin with small or no, air gaps were more susceptible to burn injuries than areas with larger air gaps, due to the absence or reduction of insulating space. However, in some areas where the largest air gap sizes occurred, greater thermal protection was not provided. This indicated that convection currents may have been initiated in these areas (Mah & Song, 2010c).

In addition to the air gap size, the contact area between a garment and the body is an important parameter especially for garments worn next to the skin, since fabric contact is closely related to sensorial comfort. In their study, Psikuta et al. (2012) measured the air gap thickness and contact area between clothing and the human body using an advanced software analysis of 3-D body scans. Their method of determining air gap size proved to be more accurate and rapid than the previously used manual or semi-manual methods. They suggest that the information provided by this new method can be used to predict and model heat and mass transfer in clothing systems.

Thermal manikin testing for full-scale garment thermal performance

Thermal manikins for the assessment of thermal insulation of garments have been used since the early 1940s. The first one-segment copper manikin was developed by US military researchers (Belding, 1949). A manikin was needed to measure the insulation properties of protective clothing and sleeping-bag systems because measurements on fabric swatches could not be accurately related to whole-body systems (McCullough, 2005).

According to Tamura (2006), a thermal manikin needs to have the following properties in order to accurately simulate the human body:

i. correct body shape and size;
ii. control of heat emission;
iii. control of the distribution of heat across the skin surface;
iv. emission of the skin;
v. control of the distribution of perspiration across the skin surface;
vi. control of pose and movement;
vii. control of core and shell differently to simulate the physiological responses of the human body.

So far, no manikin meets all these criteria (Tamura, 2006; Wang, 2011).

Heated manikins

Heated manikins refer to those manikins that are used to measure garment thermal insulation. These manikins do not simulate human sweating. Most heated manikins used nowadays are segmented. They are divided into body segments with independent temperature control and measurement. These manikins can indicate the relative amounts of heat loss from different parts of the body under specific environmental conditions and/or measure the insulation value of each segment (Nilsson, 2007).

ASTM F1291, *Standard Test Method for Measuring the Thermal Insulation of Clothing Using a Heated Manikin* (American Society for Testing and Materials, 2005a) specifies the testing procedures and results calculation. To measure the thermal resistance, a heated manikin needs to be dressed in the clothing system and placed in a cool/cold environmental chamber. Then the amount of electrical power required to keep the manikin heated to a constant skin temperature is measured under steady-state conditions. The power input is proportional to body heat loss. The total thermal insulation value is the total resistance to dry heat loss from the body surface, which includes the resistance provided by the clothing and the air layer around the clothed body (McCullough, 2005). The clothing thermal resistance R_t is measured directly with a manikin and is calculated by:

$$R_{ct\text{-}c} = (T_s - T_a)\, A/H \quad \text{eq. 2.4}$$

Where,
$R_{ct\text{-}c}$ = total thermal insulation of the clothing plus the boundary air layer (m^2 C/W),
T_s = mean skin temperature,
T_a = ambient air temperature,
A = manikin surface area (m^2), and
H = power input (W).
(American Society for Testing and Materials, 2005a)

Heated manikins have been used in determining the thermal insulation of different clothing systems, including medical clothing, firefighter turnout clothing, cold weather clothing, chemical protective clothing with cooling vests and others (Al-ajmi, Loveday, Bedwell, & Havenith, 2008; Bendkowska et al., 2010; Konarska et al., 2007; Li, Barker, & Deaton, 2007; Oliveira, Gaspar, & Quintela, 2011). General agreement with human physiological responses and higher accuracy were shown in heated manikin tests (Konarska et al., 2007; O'Brien et al., 2011). Measurements of clothing ensembles using heated manikins can account for whole body heat transfer, three-dimensional effects, layering effects, size, drape and fit, body coverage, garment closure features and dynamic effects (Al-ajmi et al., 2008; Holmer, 2004; Holmer & Nilsson, 1995; Konarska et al., 2007; Li et al., 2007; Oliveira et al., 2011). However, heated manikins do not simulate or measure heat loss from sweating, which is an important heat transfer avenue especially when ambient temperature is high or work load/duration is intensive.

Sweating manikins

There are relatively fewer sweating manikins available for measuring the evaporative resistance of clothing than heated manikins (McCullough, 2005).

Some sweating manikins are covered with a cotton knit suit and wetted out with distilled water to create a saturated sweating skin. However, the skin will dry out over time unless tiny tubes are attached to the skin so that water can be supplied at a rate necessary to sustain saturation (McCullough, Jones, & Tamura, 1989). Other manikins have sweat glands on different parts of the body. For example, sweating thermal manikin Coppelius was developed in the 1980s in a Nordic project based on the Swedish dry manikin Tore. Coppelius sweats continuously from the body surface through 187 individually controlled sweat glands (Celcar et al., 2008). One-segment sweating manikin, Walter, developed by Hong Kong Polytechnic University (Fan & Qian, 2004) used a waterproof, but moisture-permeable fabric skin, through which water vapour is transmitted from the inside of the body to the skin surface. Walter achieves a body temperature distribution similar to a person by pumping warm water from its centre to its extremities. Water is supplied automatically and the water loss by "perspiration" is measured over time. Unlike most existing manikins, Walter measures thermal insulation and moisture-vapour resistance simultaneously.

To conduct a standard sweating manikin test, the surface of the manikin is heated to skin temperature and saturated with water. The manikin is dressed in clothing, and the evaporative resistance of the clothing system is determined by measuring the power consumption of the manikin system. Testing procedures for measuring the evaporative resistance of clothing systems under two conditions, isothermal and non-isothermal, are stated in *ASTM F 2370, Measuring the Evaporative Resistance of Clothing Using a Sweating Manikin* (American Society for Testing and Materials, 2005b). In an isothermal test, the ambient air temperature is the same as the manikin's skin temperature. Even under these isothermal conditions, electrical power is required to keep the manikin at a constant temperature as moisture evaporation on the surface removes heat. The alternative protocol in the standard allows the clothing ensemble to be tested under environmental conditions that simulate actual conditions of use; this is called the non-isothermal test. The evaporative resistance determined under non-isothermal conditions is called the apparent evaporative resistance. The apparent evaporative resistance of an ensemble can only be compared to those of other ensembles measured under the same environmental conditions (McCullough, 2005).

The equation for calculating the total resistance to evaporative heat transfer provided by the clothing is:

$$R_{et-c} = [(P_s - P_a) A] / [H_e - (T_s - T_a) A/R_{ct-c}] \qquad \text{eq. 2.5}$$

Where,

R_{et-c} = resistance to evaporative heat transfer provided by the clothing and the boundary air layer,
P_s = water vapour pressure at the manikin's sweating surface (kPa),
P_a = the water vapour pressure in the air following over the clothing (kPa),
R_{ct-c} = total thermal insulation of the clothing plus the boundary air layer (°C·m^2/W),
T_s = temperature at the manikin surface (°C),
T_a = temperature in the air flowing over the clothing (°C),
A = area of the manikin's surface that is sweating (m^2) and
H_e = power required for sweating areas (W).
(American Society for Testing and Materials, 2005b).

Sweating manikins measure not only dry heat transfer but also moisture transmission. They allow comprehensive investigation of clothing thermal comfort on different clothing systems under different conditions (Celcar et al., 2008; Havenith et al., 2008; Kuklane, 2008; Li et al., 2007; O'Brien et al., 2011; Qian & Fan, 2006a; Zhou et al., 2010). Celcar, Meinander and Geršak (2008) used sweating manikin Coppelius for measuring heat and moisture transmission properties through male business clothing systems under three ambient conditions. It was noted that dry heat loss values increased with a decreasing ambient temperature while evaporative heat loss values were independent of the temperature change (Celcar et al., 2008). This result indicates that evaporation becomes the primary avenue for heat loss in hot environments. Wind speed was also found to influence the results of sweating manikin tests (Ho, Fan, Newton, & Au, 2011; Qian & Fan, 2006a, 2006b). Both thermal resistance of clothing and evaporative resistance decreased with increasing wind speed (Qian & Fan, 2006a).

Since the sweating mechanisms and construction/engineering of the sweating manikins are different, some comparative studies of these manikin systems, Walter, Tore and Newton, have been made. Walter, made of a waterproof breathable fabric “skin” filled with water, measures both thermal insulation and evaporative resistance simultaneously. However, heavy condensation has been noted in the tests with impermeable protective clothing (Zhou et al., 2010). When comparing with the results from thermal manikin, Tore, thermal insulation values obtained with Walter were significantly higher. The bias in thermal insulation caused by heavy condensation has to be corrected for using their proposed equation (Zhou et al., 2010). Wang (2008) evaluated differences between Walter and Newton in terms of the control of skin temperature, the ways of sweating, the calculation methods and the advantages and disadvantages of each. Sweating manikins are an advanced tool for use in studying clothing thermal comfort, however, they are complex and require operator expertise to correctly perform tests and interpret results.

Movable thermal manikins

Most often, manikins are used in the standing positions, but more and more researchers are attaching their manikins to external locomotion devices and measuring clothing insulation with the manikin walking (Holmer, Gavhed, et al., 1992; Kim & McCullough, 2000; McCullough & Hong, 1994; Olesen, Sliwinska, Madsen, & Fanger, 1982). Body motion increases convective heat loss and decreases the insulation value of clothing. This decreased value has been referred to as dynamic or resultant insulation. ISO 15831 (International Organization for Standardization, 2004b) gives a protocol for using a walking manikin to measure resultant insulation (McCullough, 2005).

Most of the thermal manikins mentioned above have motion capabilities. Walter’s arms and legs can be motorised to simulate walking. It was found that both thermal insulation and evaporative resistance obtained from Walter were reduced with increased walking speed (Fan & Qian, 2004). In the walking tests with Tore, similar results were reported as walking was found to result in higher heat losses (Kuklane, 2008). A two-layer movable sweating thermal manikin, JUN, was developed as a trial to compensate for the differences between conventional thermal manikins and the human body. The manikin consisted of two layers, a core section in the trunk and a shell section divided into 17 parts forming the body. The temperature and heat supply being independently controlled for each part. The posture of this manikin can be changed and it can move to simulate walking (Tamura, 2006).

Convection, induced by body motion or wind, greatly affects heat transfer and evaporative heat exchange; therefore the measurements from static conditions need to be modified by the effects of relative air velocity and body motion (Holmer, Nilsson, Havenith, & Parsons, 1999). Air permeability, garment fit, style and layering were found to be important clothing factors influencing the effects of body motion and wind speed on heat transfer and evaporative heat exchange (Qian & Fan, 2006a). Higher air permeability, looser fit, more openings and single layered clothing ensembles permit air movement and allow for convective heat loss from body motion and wind exposure.

The main advantage of manikin testing is the realistic simulation of heat and moisture transfer from the body through the clothing to the environment. This method provides objective results and repeatability is fairly high. Manikins can be used to assess the effects of air layers between the skin and clothing. If the limbs are movable, they can also be used to assess the pumping of air through the fabrics and ventilation at garment openings. They are a valuable tool to assess the influence of the clothing design on heat and moisture transfer (Rossi, 2005).

Thermal manikins are in use in the United States, Canada, France, Sweden, Finland, Norway, Denmark, Germany, United Kingdom, Switzerland, Hungary, China, Korea, Japan and other countries. A recent trend has been the development of specialized heated body parts such as a head, hand, and foot/calf so that the thermal effectiveness of the design and materials used in head gear, gloves/mittens, and footwear can be determined with more precision. The resistance values obtained in thermal manikin tests can be used in biophysical models to predict the comfort and/or thermal stress associated with particular environmental conditions and the activity of the wearer. It is important to remember that manikins do not simulate the human body physiologically. They are thermal measuring devices in the size and shape of a human being that are heated so that their surface temperatures simulate the local and/or mean skin temperatures of humans. They do not respond to changes in the environment or clothing like the human body does (McCullough, 2005).

Comfort Evaluation Using Humans

Comfort aspects that cannot be evaluated through material/garment testing

As discussed in previous chapters, extensive research has been carried out to develop methods of predicting aspects of clothing physical comfort and thermo-physiological comfort by measuring fabric properties and garment features. However, sensorial comfort and psychological comfort, by definition, are impossible to predict other than being evaluated by human subjects (Fuzek & Ammons, 1977). Even from the perspective of physical and thermo-physiological comfort, there are important characteristics of clothing which can be observed and evaluated in no other way than by having living subjects wear the clothing (Fourt & Hollies, 1970a). The following list shows the clothing measurements and human perceptions that require living subjects to determine:

- Preference;
- Acceptability;
- Perceptions related to human senses, such as touch, smell, sound etc.;
- Effect of clothing on metabolic rate/heat generation;
- Temperature and relative humidity at each surface and in each space (within each layer);
- Onset of sweating;
- Overall and local rates of sweating;
- Fraction of total sweat evaporated;
- Efficiency of cooling by the sweat evaporated;
- Effects of body movement on heat loss;
- Restrictions on body motion;
- Cost of clothing system on work performance.

(Fourt & Hollies, 1970a)

Human trials take into account all of the parameters and interactions within the clothing-human-environment system thus they have great advantages over fabric and garment tests when trying to comprehend the effects of clothing on human comfort. Disadvantages of using human subjects for comfort testing are costs, time, medical screening requirements, ethical considerations, and variability among human subjects (Barker et al., 1999; Levine et al., 1998).

All human subject research requires approval from institutional review boards and volunteer consent forms. Healthy volunteers are selected, medically screened, and acclimatized prior to the initiation of experiment trials (Selkirk & McLellan, 2004; Eves Petersen & Jones, 2002). Acclimatization, familiarization and experiment trials are usually conducted inside a climate-controlled chamber under varying environmental conditions or in the actual working environment (Montain et al., 1994; McLellan et al., 1996). Vital signs, subjective ratings and evaluations, physiological measurements and environmental data, are closely monitored during the trial to protect human subjects and for the collection of data (McLellan et al., 1996; Dorman & Havenith, 2009; White & Hodous, 1987; Derger, Jones, & Petersen, 2006).

Human trial principles

Selection of participants

When working with humans as subjects, there are many variables and considerations that must be reconciled in order to account for the variances that may be present. Selection of participants is thus very important in obtaining reliable subjective data.

Variations can be seen among a number of individual characteristics when assessing comfort using human subjects (Fuzek & Ammons, 1977; Kolich, 2003):

- Gender;
- Anthropometry(height, weight, size, etc.);
- Age;
- Health (use of medication);
- Physical fitness level (regularly exercise or not);
- Education and prior experience with the clothing;
- Cognition (ability to remember prior experiences);
- Individual aesthetical preference for colour and style of the clothing.

There are several rules in participant selection. Firstly, the participants should be volunteers. Secondly, the participants should not be associated in any technical or professional manner or employed in areas associated with fibres, textiles, etc. Thirdly and ideally, volunteers should be representative of the population that will use the particular clothing being evaluated. However, due to the consideration of cost, time and availability, some studies conducted on protective clothing have not included the end users as subjects (Dorman & Havenith, 2009; Dreger, Jones, & Petersen, 2006; Huck et al., 1997; Rissanen et al., 2008). Alternatively, young college students who had previous experience of the testing apparatus were chosen for these studies (Adams & Keyserling, 1995; Dreger et al., 2006). Information can always be collected about the participants in a study and used in the analysis to understand how those factors may have influenced their responses.

Protocol development

Human trials need to follow well-defined protocols to ensure testing consistency. Researchers normally attempt to control as many variables as possible. These include environmental conditions, type of activity, work intensity, work/rest cycles, and exposure duration (O'Brien et al., 2011). This reduces the effects from non-clothing factors so that more reliable conclusions can be drawn from the trials regarding the impact of clothing types/properties on human comfort. Protocol designs attempt to simulate actual wearing conditions. The laboratory conditions of temperature and humidity chosen to be similar to those of the expected wear environment (Montain et al., 1994; Selkirk & McLellan, 2004; White et al., 1991). The type of activity, work intensity/cycle and duration should also be matched to the end users' routine tasks, working load, shift duration etc. (Dorman & Havenith, 2009; McLellan, 2008; O'Brien et al., 2011; Rissanen et al., 2008). In some studies, more than one activity and/or workload was involved and subsequently used to evaluate different aspects of human comfort in the assessed garments (Daanen et al., 2006; White et al., 1991).

For the evaluation of heat stress or thermo-physiological comfort, a typical experimental test involves performing moderate-intensity exercise continuously for 60-90 minutes (Levine et al., 2001; McLellan, Pope, Cain, & Cheung, 1996; Montain et al., 1994). This design provides a long enough exercise session to determine the rate of heat storage during steady-state work or to determine whether steady-state can be achieved in those conditions. If the intended use of the protective clothing indicates repeated work/rest cycles, the exposure may be changed accordingly, e.g. working periods separated by rest periods (Barker & Scruggs, 1996; Selkirk & McLellan, 2004). Clothing with high insulation levels and/or low permeability may require lighter workloads to ensure the ability to perform prolonged work. Such modifications of workload and duration may be made (O'Brien et al., 2011). ASTM F 2668 *Standard Practice for Determining the Physiological Responses of the Wearer to Protective Clothing Ensembles* is one of the available standards that specify the test procedures and equipment for determining the physiological responses of subjects wearing a protective clothing ensemble (American Society for Testing and Materials, 2007b).

For the evaluations of fit, mobility, function, performance and other physical comfort aspects, task procedures and/or evaluation panels were used (Adams & Keyserling, 1995; Coca et al., 2008; Daanen et al., 2006). In task procedures, participants could be asked to perform some generalized movements (Adams & Keyserling, 1995; Coca et al., 2008; Huck, 1988; Huck et al., 1997) and/or to go through some task specific procedures (Dorman & Havenith, 2009; Rissanen et al., 2008). Results can be obtained using measurements such as joint extension/flexion (Adams & Keyserling, 1995; Huck, 1988), time needed to finish a task (Coca et al., 2008), observations by experts (Huck et al., 1997), and responses by participants regarding comfort sensations, fit, work efficiency etc. (Ashdown & Watkins, 1992; Daanen et al., 2006). ASTM F 1154 establishes two standard procedures for qualitatively evaluating the performance characteristics of chemical-protective suit ensembles in terms of comfort, fit, function, and overall integrity. Task procedure A (Table 2.5) consists of a series of movements that represent the physical movements that might be required in a work environment where these CPC are worn and which incorporate body movements that would be expected to strain the coveralls (American Society for Testing and Materials, 1999).

Physiological measurements

Methodologies and devices have been developed for measuring physiological responses such as temperature, humidity, skin pressure, sweating rate, skin wetness, oxygen consumption and heart rate (Li & Wong, 2006). Many studies have been conducted on the physiological responses of clothing comfort, especially on thermo-physiological comfort.

An important and sensitive measurement of thermal strain is core temperature. Human body core temperature is maintained around 37ºC when a person is at rest in a thermally comfortable environment. Core temperature is in dynamic equilibrium between heat exchange processes that add and subtract body heat (McArdle et al., 1996). In a study where the exercise workload is maintained at the same level, heat production can be considered constant. Therefore, core temperature can be used as an indicator of how a garment affects heat loss, heat gain, and physiological strain.

A recent method of measuring core temperature is with an ingestible telemetric core temperature pill. This technology has been demonstrated to be accurate and reliable during periods of increasing and decreasing body temperature. And it is more acceptable by participants than traditional rectal temperature probes. The pill is typically given 4-8 hours before testing to ensure that it has moved from the stomach into the intestinal tract before testing begins. Since it is not in a stable position in the body, some changes in temperature may reflect location rather than actual changes in body temperature (Kolka, Quigley, Blanchard, Toyota, & Stephenson, 1993)

Mean skin temperature plays an important role in human body heat exchange. Skin temperature is usually lower than core temperature; the presence of this temperature gradient allows body heat to be transferred from the inner body to the skin’s surface, which then dissipates to the surrounding environment through conduction, convection, and thermal radiation. As ambient temperature increases, heat loss through conduction, convection, and radiation decreases. Evaporative heat loss becomes the major means of heat dissipation, as skin is cooled by the evaporation of sweat. As long as the humidity is low, relatively high ambient temperatures can be tolerated. However, if the humidity is high or close to saturation, sweat can no longer be evaporated and cooling cannot occur. Skin temperature therefore begins to rise, with a subsequent increase in core temperature. Examination of skin temperature can provide information on when evaporative cooling starts and stops, and is therefore of great physiological significance.

Heart rate reflects both increased metabolic rate due to exercise, and increased cardiac strain due to thermal stress. Heart rate was found to be linearly related to oxygen uptake in graded exercises (McArdle, Katch, & Katch, 1996). They found that heart rate and oxygen uptake both increased as exercise intensity increased. When sweating was significant, plasma volume was reduced and the heart rate increased to compensate for the reduction. For each litre of sweat lost, the heart rate increased by 8 beats per minute (McArdle, Katch, & Katch, 1996). Heart rate was measured and recorded using an electrode band worn around the chest which transmitted a signal to a wristband receiver.

Sweating rate is important for understanding how protective clothing may affect hydration status. It is most often measured indirectly by correcting weight loss for liquids and solids ingested and excreted. Sweat capsules can be used but only measure a small surface area, and since sweating rate can vary over different regions of body, a single site does not necessarily reflect whole-body sweating rate. Both nude and dressed weights are recorded before and after every experimental exposure. Clothing weight is the difference between nude and dressed weights. Sweat accumulation in clothing can be determined from the difference between pre- and post- trial clothing weight. Actual sweat loss is determined from the difference in pre- and post- nude weights, adjusted for food and fluid intake and elimination.

Rating of perceived exertion (RPE) is defined as the degree of heaviness and strain experienced during physical work as estimated by a specific rating method. The Borg RPE Scale is an ordinal scale with values ranging from 6 “no exertion at all”, to 20 “maximal exertion” (Borg, 1982). This scale has been widely used since RPE is strongly related to many physiological measures such as heart rate, oxygen consumption, lactate accumulation, and body temperature. In some studies on clothing thermo-physiological comfort, RPE have been tested to determine whether garment type has an effect on RPE (Rissanen et al,, 2008; White et al., 1991).

Subjective rating scales

Subjective measurements are often collected to provide information on user acceptance and perceptions of comfort. At set intervals during the exposure, subjects may be asked to rate their effort and specific sensations. Additional questionnaires can be administered to collect data on garment comfort, including fit and feel (Akbarkhanzadeh, Bisesi, & Rivas, 1995). Rating scales used for subjective evaluations are an important part of obtaining useful information from test subjects. Two methods are widely used in textile research. With the first method, textiles are rated according to a subjectively defined scale. The scale is numbered from 1 to 5 with corresponding descriptions for each number, such as

1-poor, 2-sufficient, 3-average, 4-very good, and 5-excellent. The second method involves comparative sorting of textile samples from best to worst. The decision of what type of rating scale to use depends on the objectives of the study. An important limitation of using rating scales in human assessment is the small number of intervals (Winakor, Kim, & Wolins, 1980). The international standard, ISO 10551, covers the construction and use of judgment scales for thermal perception, thermal comfort, thermal preference, acceptability and tolerance (International Organization for Standardization, 1995). The standard defines two types of judgment scales: two-pole or one-pole scales. The two-pole scale, has zero as its median value with positive and negative numbers on either side. An example for rating personal thermal state consists of 9-points (-4, -3, -2, -1, 0, 1, 2, 3, 4), with negative numbers for cool or cold ratings and positive numbers for warm and hot ratings. A one-pole scale for a similar evaluation of thermal state consists of five points beginning with zero (0 comfortable, 1 slightly uncomfortable, 2 uncomfortable, 3 very uncomfortable, 4 extremely uncomfortable).

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Table 2.1 NFPA standards and levels of CBRN ensembles

Standard	1991	1992	1994		
Level	Class 1	Liquid splash	Class 2	Class 3	Class 4
Chemical barrier	Permeation	Penetration	Permeation, viral penetration	Permeation, viral penetration	Viral penetration
Chemical challenges	21 industrial + 4 warfare	5 (industrial)	5 industrial + 2 warfare	5 industrial + 2 warfare	No
Biological challenges	No	No	Blood	Blood	Blood
Vapour protection	Yes	No	Yes	Yes	No
Liquid protection	Yes	Yes	Yes	Yes	Yes
Particulate protection	Yes	Yes	Yes	Yes	Yes
Mechanical properties	Burst, Puncture propagation tear, Fitting pull out strength, Cut, Puncture, Seam strength, Cold temperature performance	Burst, Puncture propagation tear, Cut, Puncture, Seam strength, Cold temperature performance	Burst, Puncture propagation tear, Fitting pull out strength, Puncture, Seam strength, Cold temperature performance	Burst, Puncture propagation tear, Fitting pull out strength, Seam strength, Cold temperature performance	Burst, Puncture propagation tear, Fitting pull out strength, Seam strength, Cold temperature performance
Thermal protection	Flammability resistance, TPP[1], overall flash,	Flammability resistance, TPP[1], overall flash,	No	No	No
Comfort	Function	Function	Function	Function, THL[2]	Function, THL[2]

(National Fire Protection Association, 2005a, 2005b, 2007)

[1] Thermal protection performance
[2] Total heat loss

Table 2.2 ISO classification of CPC and relevant performance requirements

General performance	Specific performance test	Type of CPC					
		1	2	3	4	5	6
Whole CPC item integrity	Leak tightness	×	-	-	-	-	-
	Inward leakage	×	×	-	-	-	-
	Liquid jet test	-	-	×	-	-	-
	Liquid spray test	-	-	-	×	-	-
	Particle aerosol inward leakage test	-	-	-	-	×	-
	Limited liquid spray test	-	-	-	-	-	×
Chemical resistance of CPC material	Permeation resistance	×	×	×	×[a]	-	-
	Resistance to penetration by liquid under pressure	-	-	-	×[a]	-	-
	Liquid penetration resistance	-	-	-	-	-	×
	Liquid repellency	-	-	-	-	-	×
Mechanical and thermal properties of CPC material	Tensile strength	×	×	×	×	-	×
	Tear (trapezoidal) resistance	×	×	×	×	-	×
	Puncture resistance	×	×	×	×	-	×
	Burst resistance	×	×	×	×	-	×
	Abrasion resistance	×	×	×	×	-	×
	Flex cracking resistance	×	×	×	×	-	×
	Resistance to flame	×	×	×	×	-	×
Function	Whole suit practical performance	×	×	-[b]	-[b]	-	-[b]

(International Organization for Standardization, 2007)

[a] Either permeation resistance test or test for resistance to penetration by liquid under pressure shall be applied.

[b] Practical performance of Type 3,4 and 6 CPC is evaluated during conditioning by wearing prior to testing of the whole suit.

Table 2.3 Factors affecting comfort

Person Attributes	Fabric/ Clothing Attributes	Environment Attributes
Sex	Thickness	Air Temperature
Age	Weight	Radiant Temperature
Race	Mechanical Properties	Wind Velocity
Weight	Surface Properties	Ambient Vapour
Height	Heat Transfer Properties	Pressure
Physical Condition	Vapour Transfer Properties	
Activity	Moisture Management	
Covered Surface	Properties	
Area	Air Permeability	
	Covered Surface Area	
	Design	
	Fit	

(Branson & Sweeney, 1991)

Table 2.4 KES parameters and associated units of measure

properties	Symbols	Characteristic value	Unit
Tensile	LT	Linearity	none
	WT	Tensile energy per unit area	N/m
	RT	Resilience	%
Bending	B	Bending rigidity per unit length	$\times 10^{-4}$ Nm/m
	2HB	Moment of hysteresis per unit length	$\times 10^{-2}$ N/m
Shearing	G	Shear stiffness	N/m/degree
	2HG	Hysteresis at shear angle of 0.5°	N/m
	2HG5	Hysteresis at 5°	N/m
Compression	LC	Linearity	none
	WC	Energy required for compression	gf/cm^2
	RC	Resilience	%
Surface	MIU	mean value of coefficient of friction	none
	MMD	mean deviation of coefficient of friction	none
	SMD	mean deviation of surface roughness	µm
Weight & thickness	W	weight per unit area	g/cm^2
	TM	thickness at 50 gf/ cm^2	mm

Table 2.5 ASTM F 1154 Task Procedure A

Exercise order	Procedure
1	Kneel on left knee, kneel on both knees, kneel on right knee, stand.
2	Duck squat, pivot right, pivot left, stand.
3	Stand erect. With arms at sides, bend body to left and return, bend body forward and return, bend body to right and return.
4	Stand erect. Extend arms overhead in the lateral direction, then bend elbows.
5	Stand erect. Extend arms perpendicular to the sides of torso. Twist torso left and return, twist torso right and return.
6	Stand erect. Reach arms across chest completely to opposite sides.
7	Walk along tape[a].
8	Crawl on hands and knees along tape.

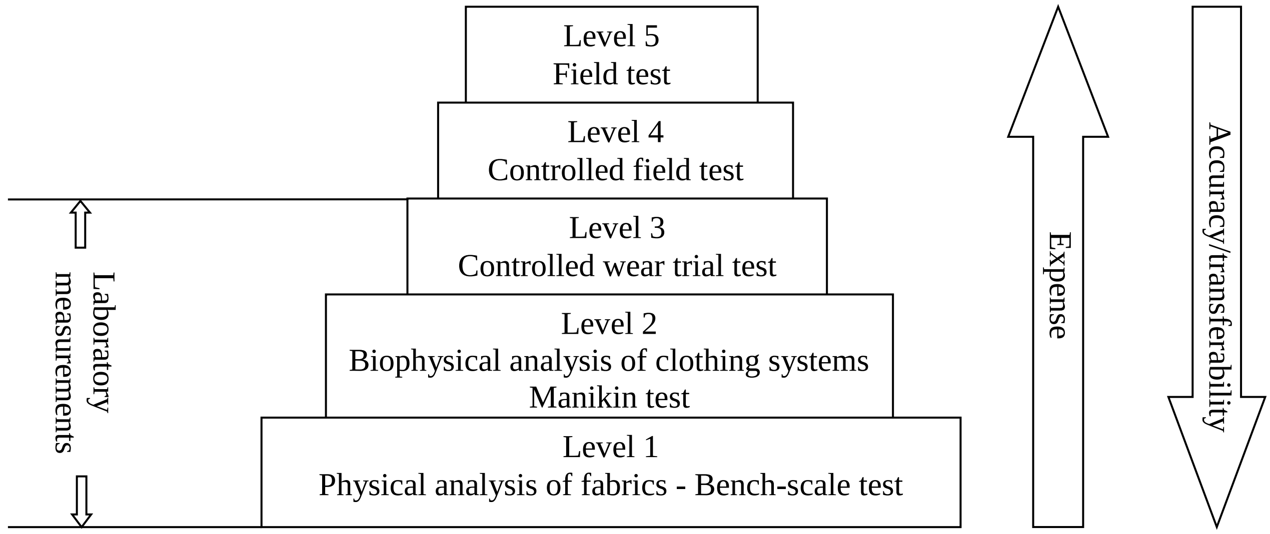

Figure 2.1 Umbach's five-level evaluation system of clothing physiological comfort

(Rossi, 2005)

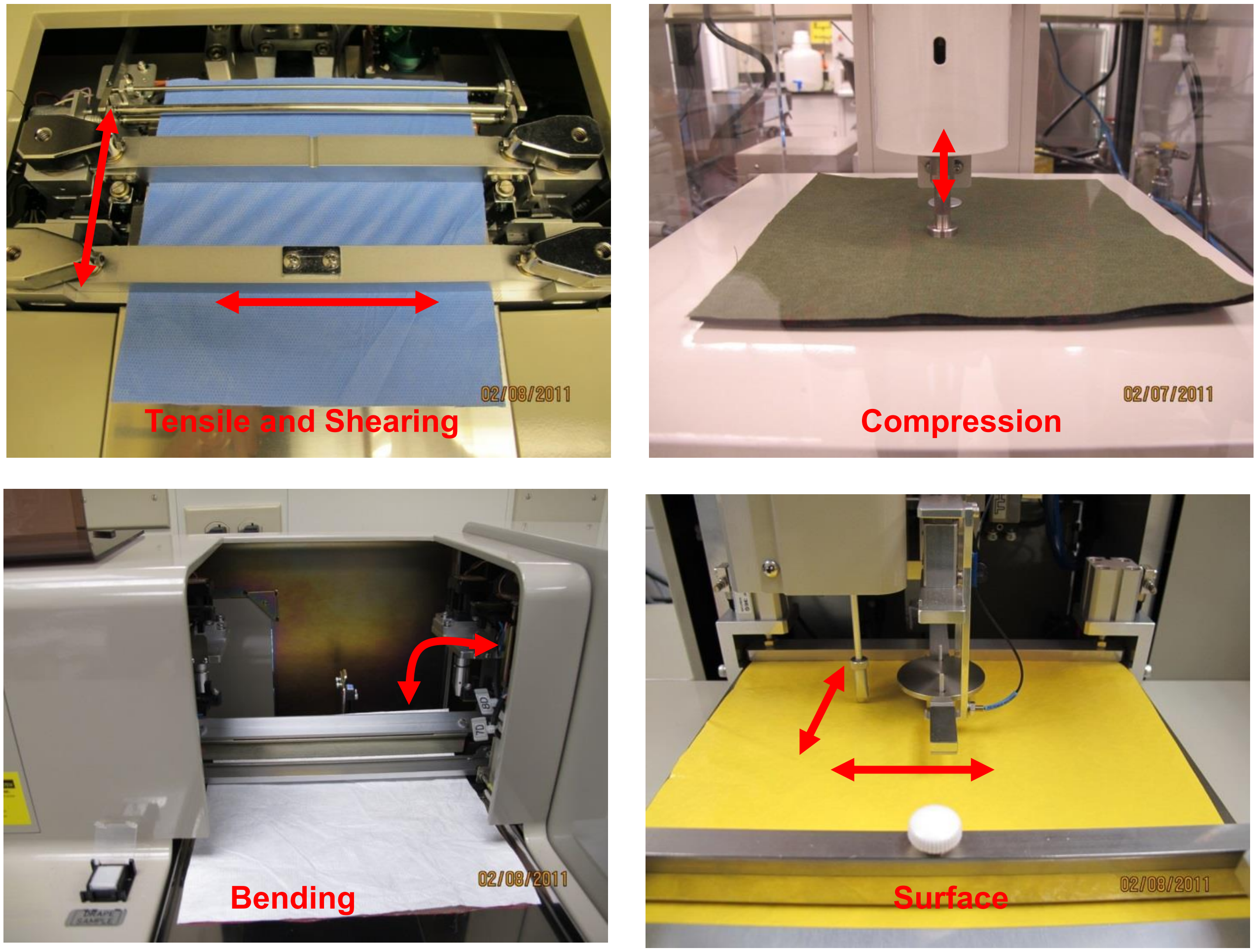

Figure 2.2 KES Testers

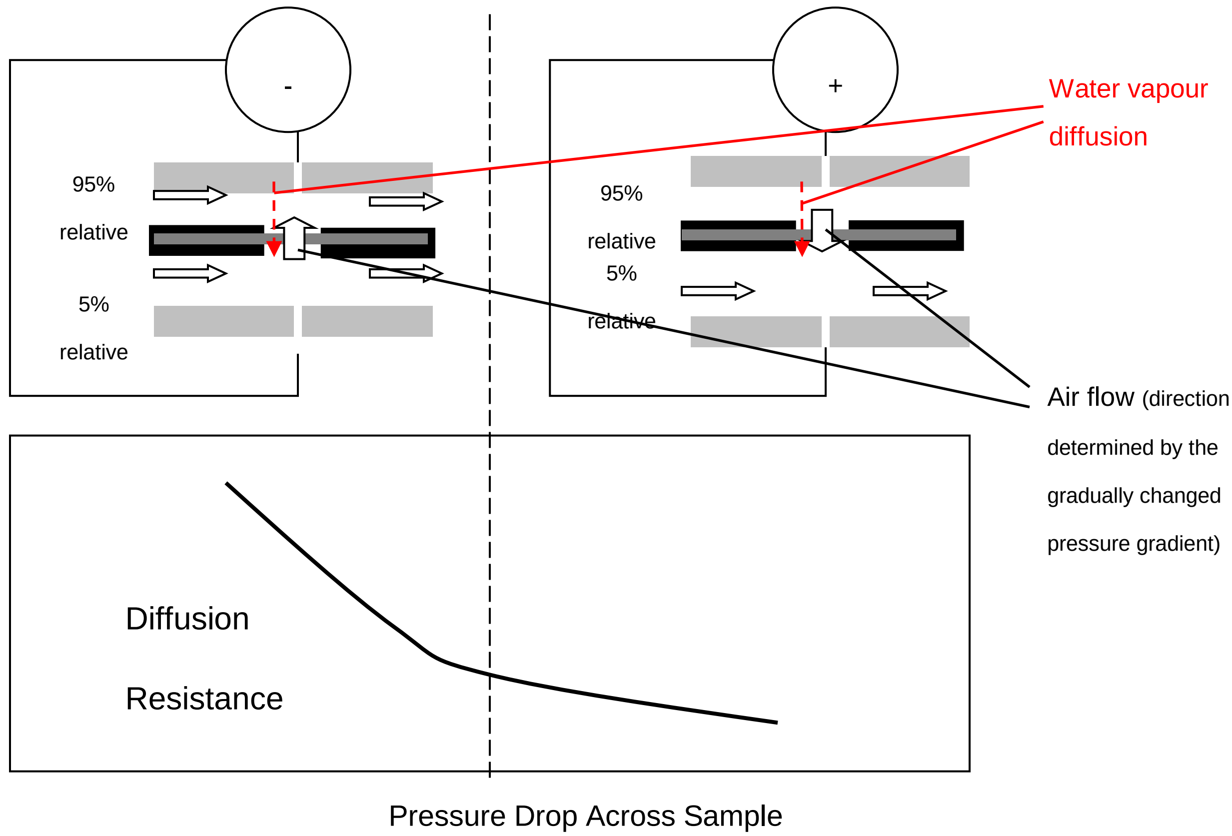

Figure 2.3 DMPC test, set-up of Part B: convection/diffusion test

CHAPTER 3 CHARACTERIZATION OF SELECTED COMFORT RELATED PROPERTIES OF FABRICS USED IN CHEMICAL PROTECTIVE CLOTHING[1]

Introduction

Comfort is a complicated mix of subjective sensations. According to Slater (1985), comfort involves physiological, psychological, and physical aspects. Psychological comfort is related to the subjective opinion of the clothing wearer and is therefore impossible to evaluate objectively. Physiological comfort also referred to as thermo-physiological comfort or thermal comfort, relates to the way clothing buffers and dissipates moisture and heat (Slater, 1985). In addition to environmental conditions, garment features and the wearer's activity level, many researchers agree that the thermal and moisture transfer properties of the clothing materials significantly influence physiological comfort (Barker & Scruggs, 1996; Branson & Sweeney, 1991; Fourt & Hollies, 1970; Havenith, 1999; Saville, 1999). These material properties include thickness, weight, thermal insulation, resistance to evaporation, and air permeability. They have been used effectively to compare the comfort related performance of different conventional fabrics, fabrics for sportswear and workwear and materials for thermal protective clothing (McCullough et al., 2005; Rego et al., 2010; Xu, McQueen, Strickfaden, Aslund, & Batcheller, 2012; Yoo & Barker, 2005). The investigation and characterization of physiological comfort related fabric properties of chemical protective garments is limited.

Physical comfort is correlated with the interaction of the clothing with the senses of the wearer (Fourt & Hollies, 1970; Slater, 1985). Physical comfort is essentially a result of how much physical stress is generated in the fabric during wear and how stress is distributed over the skin and to the muscles. Skin tactile sensations such as prickliness, itchiness, stiffness, and smoothness are determined by the mechanical properties of the fabric or fibre and can be predicted by

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[1] *A version of this chapter is published in Performance of Protective Clothing and Equipment: Emerging Issues and Technologies STP 1544.*

Reference: Wen, S., Song, G., & Ducan, S. (2012). Analysis of physical and thermal comfort properties of chemical protective clothing. In A. M. Shepherd (Ed.), Performance of Protective Clothing and Equipment: Emerging Issues and Technologies STP 1544 (pp. 48-73). West Conshohocken, PA: ASTM International.

mechanical simulation of skin/fabric interaction (Kilinc-Balci, 2010). Physical comfort includes not only the feel of the fabric against the skin but the physical burden (weight, restriction to motion) of the whole garment (Ashdown, 2011; Huck, 1988). When the physical comfort of protective clothing is discussed, physical burden is a more dominant aspect than tactile sensations because most protective garments are not worn in direct contact with the skin. When an individual is working, the physical burden he/she encounters includes the weight of the fabric, friction between garment surfaces, and physical strains caused during stretching, bending, and shearing of the fabric (Adams & Keyserling, 1995; Rissanen et al., 2008). The heavier, rougher and stiffer the fabric, the greater is the physical burden. Therefore, the physical comfort associated with wearing CPC has a strong relationship to the mechanical and surface properties of the fabric. There have been attempts to investigating physical comfort based on fabric mechanical and surface properties (Barker & Scruggs, 1996; Cowan et al., 1988; Yoo & Barker, 2005). Most of these studies focused on predicting subjective hand and skin tactile sensations. No literature was found that addressed physical burden (restriction to motion) based on fabric mechanical properties.

Given that certain textile properties are known to contribute to physiological and physical comfort, it should be possible to predict how a garment will affect comfort based on its material properties. In this study several bench scale fabric test methods were chosen to characterize the physiological and physical comfort of selected CPC materials. A sweating guarded hot plate and a dynamic moisture permeation cell (DMPC) were used to assess the transfer of heat and moisture through the test materials under standard conditions. The Kawabata Evaluation System (KES) was used to measure fabric mechanical and surface properties in order to predict the physical burden the wearer would experience from each of the materials.

Materials and Methods

Materials

Six fabrics made from different materials and providing different levels of protection were investigated. Three materials were multi-layer and three were single layer or laminated single layer. The material characteristics of the fabrics are outlined in Table 3.1. Fabrics Proshield®, Tyvek®, Tychem®, Cold and Gulf were available in hooded coveralls with a front zipper. Industrial coveralls made from Proshield®, Tyvek® and Tychem® had identical garment design with elastic at the edges of the hood, wrists, and ankles. Military coveralls, Cold and Gulf, had more detailed garment designs, including pockets on chests, thighs, and upper arms, and Velcro® fasteners at wrists and ankles. Gulf also had a belt. The garment design for the Prototype fabric was still under development and the tested material was received in swatches (25 cm × 40 cm). Sketches of the garment designs are shown in Appendix 1. The six fabrics were selected to cover a variety of material types and protection levels for different applications. There are many industrial CPC available on the market with different designs, such as two-piece systems, coveralls without hood, and totally encapsulated coveralls. The open-face hooded coveralls were chosen because they were similar in design to the military coveralls. Styling similarity and comparability were taken into consideration for the fabric testing of the current study, but were more important for the garment analyses and human wear trial investigations of the subsequent studies.

Specimens for testing (except Prototype) were cut from the coveralls following the sampling rule that no two specimens for the same test contain the same warp and weft yarns or same lengthwise or crosswise components for non-woven materials. The fabric specimens were conditioned according to ASTM D 1776 at 21 ± 1 ºC and 65 ± 2% relative humidity for at least 24 hours prior to testing unless otherwise specified.

The mass per unit area was measured by weighing five die cut specimens according to test method CAN/CGSB-4.2 No.5.1-M90 (Canadian General Standards Board, 2004). Fabric thickness, under 1.0 kPa pressure, was measured according to CAN/CGSB-4.2 No.37-2002 (Canadian General Standards Board, 2002).

Methods

Fabric Mechanical and Surface Properties

The Kawabata Evaluation System (KES) has been used widely for testing fabric tactile qualities, such as stiffness, thickness, extensibility, appearance retention and surface smoothness (Avinc et al., 2010; Jeguirim et al., 2010; Lam et al., 2011; Liu et al., 2010) and providing “total hand” values for the evaluation of fabrics for specific end uses (Kawabata, 1980; Radhakrishnaiah et al., 1993). In a few studies (Behera, Ishtiaque, & Chand, 1997; Cardello et al., 2003; Sztandera, 2008), fabric mechanical and surface property data from KES tests were interpreted to predict tactile comfort of the fabrics. In this study, the KES was used to determine the tensile, shearing, bending, compression, surface friction, and roughness properties of the CPC fabrics. Three to five replications were completed for each test. For multi-layered fabric systems, shell and inner layers were tested separately in the tensile, shearing and bending tests. Shell fabric and inner layers were tested as one fabric system in compression and surface tests. Woven fabrics were tested in their lengthwise dimension only.

Air Permeability

The air permeability of the fabric systems was measured in accordance with ASTM D 737 (American Society for Testing and Materials, 1996). The testing device used in this experiment was a Frazier high-pressure air permeability apparatus. The air pressure differential was adjusted to 12.7 mm of water (125 Pa) for the test. Ten specimens of each sample were tested.

Thermal resistance (R_{ct}) and evaporative resistance (R_{et})

The thermal resistance R_{ct} and the evaporative resistance R_{et} of each fabric system was determined using a Measurement Technology Northwest sweating guarded hot plate (Figure 3.1) in an environment of 25°C and 65% relative humidity, according to the test procedures described in Part C of ASTM F 1868-09 (American Society for Testing and Materials, 2009). Three to five specimens were tested for Proshield®, Tyvek®, Tychem®, Gulf and Cold. Prototype was not tested by this method due to the limited size and amount of the fabric received.

Dynamic moisture permeation cell (DMPC)-diffusion/convection test method

Air permeability, water vapour diffusion, and water vapour transmission rates were tested according to ASTM Standard F2298: Standard Test Methods for Water Vapour Diffusion Resistance and Air Flow Resistance of Clothing Materials Using the Dynamic Moisture Permeation Cell, Part B: Convection/diffusion Test. The test conditions are listed below.

Temperature = 30°C

Sample area = 10 cm^2

Flow rates on top and bottom = 2000 cm^3/minute

Humidity on top = 0.95 (95%); humidity on bottom = 0.05 (5%)

Pressure drop varied in increments between approximately –150 Pa and 150 Pa.

This test method was used as a supplement to the hot plate R_{et} test. Only one specimen was tested for each fabric system.

Statistical analysis

Descriptive statistics including the mean (M), standard deviation (SD), coefficient of variation in percent (CV%), and ranges (minimum and maximum values) were determined for data from KES testing, R_{ct} , R_{et}, total heat loss (THL) and air permeability using SPSS (version 21.0). One-way ANOVA was used to compare the tensile, bending, shearing, compression and surface properties, and R_{ct} , R_{et}, THL and air permeability of different material types. For all tests a significance level of $p \leq 0.05$ was used. Where significant effects or interactions were found, post-hoc comparisons using the Tukey HSD test were made to locate significant differences.

Results and Discussion

Fabric mechanical and surface properties

The mean values (±SD) of sixteen parameters measured in KES tests are shown in Table 3.2. These values describe the mechanical and surface properties of the fabric systems. For tests performed on the shell and inner layer separately, results for both layers were listed.

Tensile properties

In the tensile test, tensile linearity (LT), tensile energy (WT), and tensile resilience (RT) were evaluated. LT is the linearity of the stress-strain curve, which reflects the elasticity of the fabric (Kawabata, 1980). A higher value of LT represents a stiffer fabric. Tensile work, WT is defined as the energy required to extend a fabric or the ability of a fabric to withstand external stress during extension. Tensile resilience, RT is defined as the ability of a fabric to recover after the application of tensile stress. It is a measure of the percentage of energy recovery from tensile deformation (Kawabata, 1980). A low fabric RT value implies that the fabric will have difficulty recovering to its original shape after the release of the applied tensile stress. In regard to CPC, fabrics with high WT and RT values, together with low LT values, possess excellent tensile strength and reasonable stretchiness to allow movement. As shown in Figure 3.2, fabric system Gulf has the lowest LT and relatively high WT and RT values, thus the comfort related tensile properties of fabric Gulf are good. Fabric system Cold is stronger and stiffer than the other fabrics. It has the highest WT and LT values of the fabrics tested. Fabric Tyvek®, with a low RT value of 45.7%, is the fabric mostly likely to lose its shape due to tensile stress. The tensile and recovery behaviours of these fabric systems can also be compared with load-elongation curves, as demonstrated in Figure 3.3. The curves of fabric Tyvek® lying to the right of the others suggest its high extensibility, which would be an advantage in terms of the freedom of motion of the person wearing this garment. The curve for fabric Tychem® being on the very left of the chart shows that it has the least extensibility of all the fabrics and may restrict movement of the wearer. Compared with the other fabrics, fabric Tyvek® has low tensile resilience and thus low appearance retention. This can affect both aesthetics and fit if the fabric is used to construct reusable CPC.

Bending properties

Bending rigidity (B) is defined as the ability of a fabric to resist the bending moment. Bending hysteresis (2HB) is defined as the recovery ability of a fabric after being bent. Bending properties affect both the handling and flexibility of a fabric; bending rigidity is related to the quality of stiffness when a fabric is handled. A higher B value indicates greater resistance to being bent. Generally, a fabric with low bending rigidity (B) and low bending hysteresis has good bending properties (Lam et al., 2011).

As described in Figure 3.4 and Figure 3.5, fabric Tychem® has extremely high B and 2HB values compared to the other fabrics tested. This indicates that fabric Tychem® is hard to bend, and once bent it is hard for fabric Tychem® to recover its original shape. Since walking, lifting, etc., require bending of the fabric, fabric Tychem® would be expected to resist these movements placing a large mechanical burden on the wearer.

Shearing properties

Shear rigidity G is defined as the ability of a fabric to resist shear stress. Shear rigidity of a fabric depends mainly on the mobility of the warp/weft yarns within the fabric (Kawabata, 1980). Lower values indicate less resistance to shearing corresponding to a softer material having better drape (Kawabata, 1980; Lam et al., 2011). In a KES standard measurement, 2HG and 2HG5 are the hysteresis of shear force at 0.5º and 5º respectively. Shear hysteresis is the ability of a fabric to recover after receiving the shearing stress. The lower the shear hysteresis the better the recovery will be. Therefore, fabric with low shear stiffness (G) and low shear hystereses has superior shearing properties, since it is does not resist shearing forces and recovers readily (Kawabata, 1980).

As presented in Figures 3.6 and 3.7, the shearing behaviours of the Tychem® and Cold fabrics are different from the other fabrics tested. With the highest G, 2HG, and 2HG5, the Tychem® fabric has the highest resistance to shearing of all the fabric systems tested. That is, to perform movements that involve shearing of the fabric, the highest physical work will be needed when wearing CPC consisting of Tychem®. Fabric systems Proshield®, Tyvek®, Gulf and Prototype had better shearing properties. The higher G, 2HG and 2HG5 of Cold compared to fabrics Proshield®, Tyvek®, Gulf, and Prototype is mainly due to the adsorbent layer. The adsorbent layer is foam coated with carbon, which does take more force to shear; however, the recovery of this foam from shearing is not as good as the recovery of woven fabrics. Therefore, the overall shearing behaviour of the Cold fabric is relatively poor.

Compression properties

The compression properties of the tested fabric systems included compressional linearity (LC), compressional energy (WC), and compressional resilience (RC) (Kawabata, 1980). These were measured at three distinct points on the specimens (composite fabrics were measured as a whole). Results for LC, WC, and RC are shown in Figure 3.8. Compression linearity LC shows the linearity of a compression-thickness curve. A high LC value indicates a solid material with low compressibility. Compressional energy WC is the work done in compressing a fabric. In the test, the compressing force is set to 50 gf/cm^2 for all the fabrics. At this same force, when a fabric is more easily compressed, the compressional sensor travels a greater distance. Therefore the higher the value of

WC, the greater the compressibility of the fabric. In addition, compressional resilience (RC) is defined as the ability to retain the fullness of the fabric after being compressed. The RC indicates the recoverability of the fabric after the compression force is removed. A high value of RC indicates good recovery from compression. Fabric with good compression properties usually possesses higher LC, WC, and RC values; compressional properties are highly dependent on the thickness of the fabric. From Figure 3.9, we see that at the same compressional load, fabrics Tychem®, Cold, and Gulf are compressed more easily than fabrics Prototype, Tyvek®, and Proshield®. The reason that Cold and Gulf can be compressed by about 1 mm is due to the adsorbent layer that increases their thickness. Fabric Tychem® is a single layer laminated nonwoven sheet. The exterior surface of the material is smooth and flat, however, the back is a fluffy layer of fibre batting. The loft of the nonwoven structure accounts for the compressional behaviour of Tychem®.

Surface properties

Fabric surface properties including the coefficient of friction (MIU), the mean deviation of coefficient of friction (MMD) and geometrical roughness (SMD) were measured. The MIU is the force required to move two surfaces over each other divided by the force holding them together; the former force is reduced once the motion has started. That is, the higher the value of the MIU, the greater the friction force necessary to slide the fabric surface over an object. The SMD measures the geometrical roughness of the fabric surface, or the fabric surface evenness characteristic (Kawabata, 1980). The lower the SMD value, the more even the fabric surface will be. Generally, fabrics with low MIU and SMD values have surface properties more compatible with CPC. In this respect, fabrics Proshield® has better surface properties than the other fabrics tested since it has lower MIU and SMD values, as listed in Table 3.2. Fabrics Tyvek® and Tychem® have relatively good surface roughness (relatively smooth); however, the friction coefficients of these two fabrics are higher than those of Proshield®, Gulf, and Prototype. Friction between garment surfaces, including the dragging between different layers and the rubbing against the same fabric surface (e.g., sleeves rubbing on side of the body), can be a physical burden when the wearer is involved in low intensity activities. Fabric Cold has a high MIU and a high SMD, therefore, the surface properties of Cold is poor. Although fabric Prototype has a low MIU, it has the highest surface roughness of the fabrics tested. This is because of its relatively low fabric count (Table 3.1) that makes the fabric structure open with large spaces between yarns and an uneven surface contour.

Overall physical comfort

In the KES testing manual (Kawabata, 1980), the total hand value is defined to give an overall assessment of the test fabric. Total hand value is a numerical scale, from 0 (poor) to 5 (excellent), which is an evaluation of the primary quality of fabrics concerned with comfort and appearance (Kawabata, 1980).The total hand value is correlated to and calculated based on the mechanical and surface properties of hundreds of sample fabrics (Kawabata, 1980). It is a good indicator of the feel of fabric for some conventional end uses, for example, men's winter suits and women's summer dresses (Radhakrishnaiah et al., 1993; Rego et al., 2010). However, material properties for CPC deviate greatly from those of conventional fabrics; the total hand value defined by Kawabata does not represent the overall physical comfort quality of CPC materials.

A multi-axis radar graph, Figure 3.10, was plotted based on tensile linearity (LT), bending rigidity (B), shearing stiffness (G), surface roughness (SMD), and fabric mass (W). As discussed above, CPC materials with high LT, B, G, SMD, and W will be stiff, rigid, rough, and heavy, thus contribute negatively to the physical comfort of the worker. In Figure 3.10, the five properties of the six fabrics were marked along the corresponding axes. The value used on each axis was the relative value. The relative value was defined as the ratio of the true value of a fabric over the maximum value among the group. For example, the relative W of fabric Gulf was calculated as 478 (the unit mass of Gulf)/ 533 (maximum unit mass among the six fabric systems) = 0.90. The five marked relative values of each fabric form a pentagon. By comparing pentagon areas, we can obtain the relative overall physical comfort ranking of these fabrics. Fabric Tychem® had the largest pentagon in the chart; therefore, it is predicted to perform the worst in physical comfort. The multi-layered fabrics Cold, Prototype, and Gulf, had lower overall performance because of their heavier weight, high elasticity and poor surface properties. The light-weight, single layered fabrics Proshield® and Tyvek® are expected to present less physical burden on the wearer than the other fabrics tested.

Heat and moisture transfer properties

Air permeability

The mean values (±SEM) of air permeability for the six fabric systems are displayed in Figure 3.11. Among the fabric systems, the multi-layered fabric system Cold had the highest air permeability at 41.34 $cm^3/cm^2/s$ and the laminated nonwoven Tychem® and single layer nonwoven Tyvek® had the lowest air permeability at zero and 0.15 $cm^3/cm^2/s$. All fabric types were significantly different from each other except that Proshield® did not differ from Gulf and Tyvek® did not differ from Tychem® (Figure 3.11). The ability to transfer air and vapour is an important component of a comfortable fabric. The air permeability of the fabrics influenced their thermal and evaporative resistance properties as will be discussed in following paragraphs.

Thermal resistance (R_{ct})

Thermal resistance results from the sweating guarded hot plate tests for fabrics Proshield®, Tyvek®, Tychem®, Gulf and Cold are listed in Table 3.3. Among the CPC materials being investigated, the thickest multi-layered material Cold was found to have the highest R_{ct} at 0.151 $m^2 \cdot K/W$, $p<0.05$. For the thin and permeable fabric Proshield®, R_{ct} was significantly lower than the thicker fabric systems, Cold, Gulf and Tychem®. A still air layer, in which air movement does not take place, provides significant thermal insulation, and contributes to the total thermal resistance of a fabric system. When a Pearson's r test was conducted, R_{ct} was found to be correlated to fabric thickness, $r = 0.883$, $p<0.01$, indicating that the thicker fabrics normally had higher thermal insulation. This is because for most clothing materials the volume of air enclosed is far greater than the volume of the fibres (Havenith, Holmer, Den Hartog, & Parsons, 1999). Therefore, thermal insulation is very much dependent on the thickness of the material and less dependent on fibre type. Another factor influencing R_{ct} is the air permeability of the material. Air flow through permeable fabric layers makes heat loss by convection easier than in the impermeable fabric systems. Tyvek®, was the thinnest material tested (0.18 mm), yet its R_{ct} was not lower than the thicker fabric Gulf (1.10 mm) possibly due to the fact that the air permeability of Tyvek® (0.15 $cm^3/cm^2/s$) was considerably lower than the air permeability of Gulf (18.2 $cm^3/cm^2/s$).

Evaporative resistance (R_{et})

Tychem® had the highest R_{et} at 46.9 $m^2 \cdot KPa/W$ among all of the fabrics, $p<0.05$. Evaporative resistance of Cold (16.7 $m^2 \cdot KPa/W$) was higher than Proshield® and lower than Tychem® but not different from Gulf and Tyvek®. For most woven or nonwoven permeable fabrics, the pathway of water vapour transport is through the air spaces in the fabric (Gibson, 1993). Resistance to the transport of water vapour through the fabric is thus mainly determined by the thickness of the enclosed air or the thickness of the fabric. Coatings, membranes, or other treatments added to the fabrics have a major effect on evaporative resistance, as vapour molecules must diffuse through the treated material (Havenith et al., 1999). The results of R_{et} were consistent with the theories described above. Fabrics Proshield®, Tyvek® and Gulf, all relatively thin and permeable, had lower R_{et} values, while fabric Cold and the impermeable fabric Tychem®, affected by thickness and the laminated coating, were found to have higher evaporative resistances.

Appendix 2 lists the fabric thermal insulation (R_{ct}) and evaporative resistance (R_{et}) results from the sweating guarded hotplate tests.

Total heat loss (THL)

To evaluate the fabrics from the point of view of overall thermal comfort, total heat loss (THL) was calculated and reported in Table 3.3 according to ASTM F 1868, Part C. Single layer permeable fabric Proshield® had the highest THL at 151.8 W/m^2, while the thickest multi-layer fabric Cold had the lowest THL at 75.0 W/m^2. The remaining tested fabrics Tyvek®, Tychem® and Gulf had a THL higher than Cold but lower than Proshield®, $p<0.05$. Proshield® having the highest THL value allows heat and moisture transfer through the fabric at the highest level among these fabric types; thus it is predicted to perform better (less heat stress) than the other fabrics. Fabric Cold, with the lowest THL value, prevents combined heat dissipation through heat and moisture transfer to the environment. More heat will be retained in CPC made from this type of fabric.

DMPC-diffusion/convection properties

A good correlation ($r = 0.993$, $p<0.01$) was found between the test results for water vapour diffusion resistance from the DMPC (Table 3.4) and R_{et} values obtained in the sweating hot plate tests. The air permeability calculated using the

DMPC is also highly consistent with the results from ASTM D737. The DMPC is a much quicker test than the sweating hot plate (R_{et}) test. The other advantage is the DMPC test specimen is much smaller. The prototype fabric was found to have a lower water vapour diffusion resistance than the other two multi-layer fabrics and is therefore predicted to have better thermal comfort than Gulf and Cold, especially when worn in hot environments or for high intensity work where evaporative heat transfer is the main avenue of heat loss.

The diffusion/convection test comprises a series of measurements at different pressure gradients which allows the determination of the relationship between the water vapour diffusion resistance and the pressure drop. For fabric Tyvek®, the relationship between vapour diffusion resistance and pressure drop was almost linear (Figure 3.12). For fabric Cold, on the other hand, diffusion resistance dropped dramatically within the pressure drop range of -2 and -1 Pa. The change of vapour diffusion resistance became much slower when the pressure dropped to less than -1 Pa. That is, the moisture transfer property of Tyvek® does not change dramatically due to the change of the environmental air pressure, while the moisture transfer property of Cold is sensitive to the environmental air pressure. Especially when a negative air pressure is present, Cold quickly becomes more moisture permeable. This information has implications for the evaluation of thermal comfort of CPC in some specific environments (e.g., negative air pressure clean rooms and environments with strong winds) where air flow (pressure) is an important element.

Conclusions

Physical and thermal comfort properties were assessed for six CPC materials using bench-scale test methods. The six fabrics showed significant differences in low-stress mechanical and surface properties obtained from KES tests. Differences in physical properties reflect differences in the level of physical burden on the CPC wearer during movement. The mechanical properties were analyzed and summarized in a radar graph. Based on this predictive radar graph, the physical burden of garments made from these fabrics was predicted as: Tychem® > [Cold, Gulf and Prototype] > [Tyvek® and Proshield®]. Thermal and evaporative resistance, air permeability, and DMPC diffusion/convection were tested to characterize the heat and water vapour transfer properties of the fabrics. Correlation was found between R_{et} as measured on a hot plate and water vapour resistance measured by the DMPC test. The thermal comfort performance from most comfortable to lest comfortable for the six CPC fabrics was predicted based on the THL results as follows: Proshield® > [Tyvek®, Gulf and Tychem®] > Cold.

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Table 3.1 Description of the fabric systems used in this study

Fabric type	Structure	Fiber content	Fabric construction	Mass (g/m^2)	Thickness (mm)
Proshield®	Single layer	55%polyester /45% polyethylene	nonwoven	55	0.25
Tyvek®	Single layer	100% high density polyethylene	nonwoven	45	0.18
Tychem®	Laminated single layer	Proprietary multi-layer barrier film laminated to nonwoven substrate	laminated nonwoven	257	0.58
Gulf	Multi-layer	Shell: 50% nylon/ 50% cotton Adsorbent: activated carbon woven cloth (pyrolised polyacrylonitrile) bonded to nonwoven Inner layer: 100% nylon	Shell: plain weave, fabric count 23×20 Inner layer: plain weave rip-stop variation	478	1.10
Prototype	Multi-layer	Shell: proprietary woven Adsorbent: proprietary carbon coated on knit fabric	Shell: plain weave, fabric count 23×11 Adsorbent: beaded carbon coated on tricot knit fabric	278	0.93
Cold	Multi-layer	Shell: 50% nylon/ 50% cotton Adsorbent: open cell carbon impregnated foam	Shell: plain weave, fabric count 25×20 Adsorbent: foam bonded to tricot knit	533	2.62

Table 3.2 Mechanical properties (mean ± SD) measured using the Kawabata Evaluation System (N=3)*

Fabric Type		Proshield®	Tyvek®	Tychem® N=5	Gulf	Prototype	Cold
Tensile	LT	0.737±0.021	0.776±0.032	0.796±0.021	0.712±0.014 0.676±0.013*	0.745±0.029 0.687±0.009	0.778±0.007 0.916±0.018
	WT (N/m)	4.29±0.62	6.58±0.90	2.82±0.26	3.15±0.07 5.19±0.13	2.74±0.05 3.14±0.08	3.31±0.29 10.59±0.36
	RT (%)	85.7±5.3	45.7±3.7	90.3±1.4	80.8±1.1 64.2±0.8	88.1±0.9 90.6±1.3	78.3±0.7 55.9±0.3
Bending	B (x10^{-4}Nm/m)	0.155±0.037	0.128±0.020	4.26±0.21	0.268±0.062 0.445±0.030	0.511±0.045 0.346±0.251	0.493±0.013 1.32±0.61
	2HB (x10^{-2} Nm/m)	0.096±0.019	0.193±0.058	2.29±0.17	0.200±0.049 0.631±0.039	0.166±0.060 0.322±0.003	0.266±0.028 1.37±1.24
Shearing	G (N/m/degree)	4.10±0.68	5.29±0.36	32.0±2.5	2.23±0.27 3.18±0.26	2.61±0.35 6.68±0.32	3.88±0.05 14.6±2.9
	2HG (N/m)	3.09±0.45	6.57±0.84	31.3±6.2	2.28±0.26 5.82±0.51	3.32±0.38 8.05±0.51	4.65±0.02 27.6±1.2
	2HG5 (N/m)	17.5±1.9	21.7±1.2	91.9±2.1	8.36±0.40 9.20±0.65	9.10±0.99 29.3±0.8	15.2±0.4 93.5±0.4
Compression	LC	0.387±0.019	0.300±0.037	0.204±0.047	0.338±0.016	0.408±0.032	0.261±0.021
	WC (gf/cm^2)	0.154±0.013	0.153±0.047	0.604±0.041	0.637±0.041	0.394±0.002	0.397±0.018
	RC (%)	62.0±2.2	39.0±9.9	52.3±5.5	42.2±2.1	51.5±0.5	46.6±0.9
Surface	MIU	0.151±0.004	0.210±0.010	0.192±0.007	0.187±0.009	0.146±0.004	0.189±0.004
	MMD	0.0052±0.0009	0.0103±0.0013	0.0095±0.0014	0.0106±0.0005	0.0100±0.0020	0.0178±0.0010
	SMD (µm)	1.95±0.38	2.40±0.17	1.23±0.26	4.18±0.81	10.0±0.8	5.10±1.47
Thickness	Thickness at 5gf (mm)	0.42±0.01	0.52±0.14	1.93±0.32	1.97±0.02	1.35±0.04	3.44±0.05
	Thickness at 50 gf (mm)	0.26±0.00	0.18±0.01	0.70±0.01	1.21±0.01	0.96±0.01	2.83±0.03

*The highlighted values are the results of testing on the inner layers of the multi-layer materials.

Table 3.3 Thermal and evaporative heat transfer properties*

Fabric	Thermal resistance, R_{ct} (m^2K/W)	Evaporative resistance, R_{et} (m^2KPa/W)	Total heat loss, THL (W/m^2)
Proshield®	0.0823±0.0023 $^{c\ d\ f}$	7.80±0.77 $^{c\ f}$	151.8±5.6 $^{b\ c\ d\ f}$
Tyvek®	0.104±0.0058 ^{f}	14.0±1.45 ^{c}	114.7±7.4 $^{a\ f}$
Tychem®	0.108±0.0012 $^{a\ f}$	46.9±3.06 $^{a\ b\ d\ f}$	108.2±1.5 $^{a\ f}$
Gulf	0.108±0.0038 $^{a\ f}$	10.8±0.36 ^{c}	109.3±4.3 $^{a\ f}$
Cold	0.151±0.0082 $^{a\ b\ c\ d}$	16.7±0.92 $^{a\ c}$	75.0±4.8 $^{a\ b\ c\ d}$

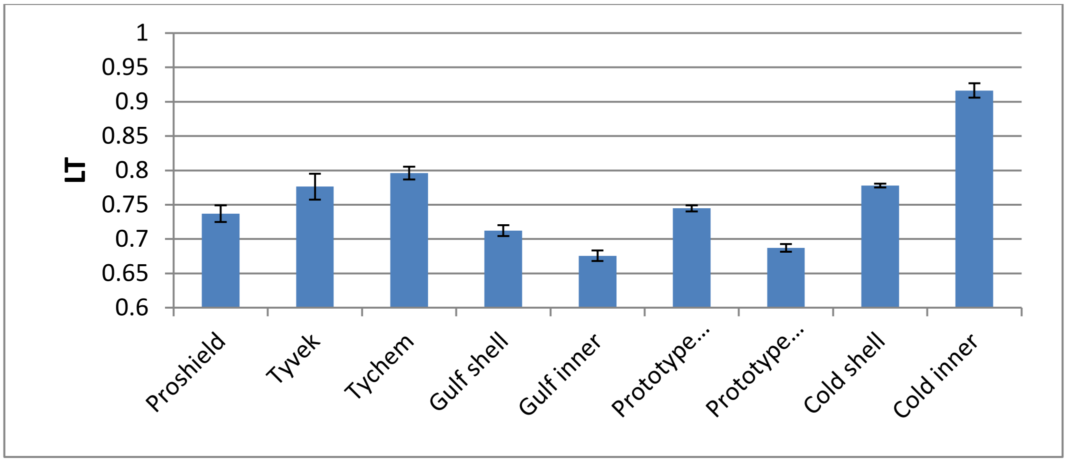
*Because the amount and size of received multi-layered fabric P was limited, sweating hot plate tests were not performed on this fabric.

Values are means ± SEM.
Abbreviations:
^{a} = different from Proshield®, $p<0.05$; ^{b} = different from Tyvek®, $p<0.05$;
^{c} = different from Tychem®, $p<0.05$; ^{d} = different from Gulf, $p<0.05$;
^{f} = different from Cold, $p<0.05$;

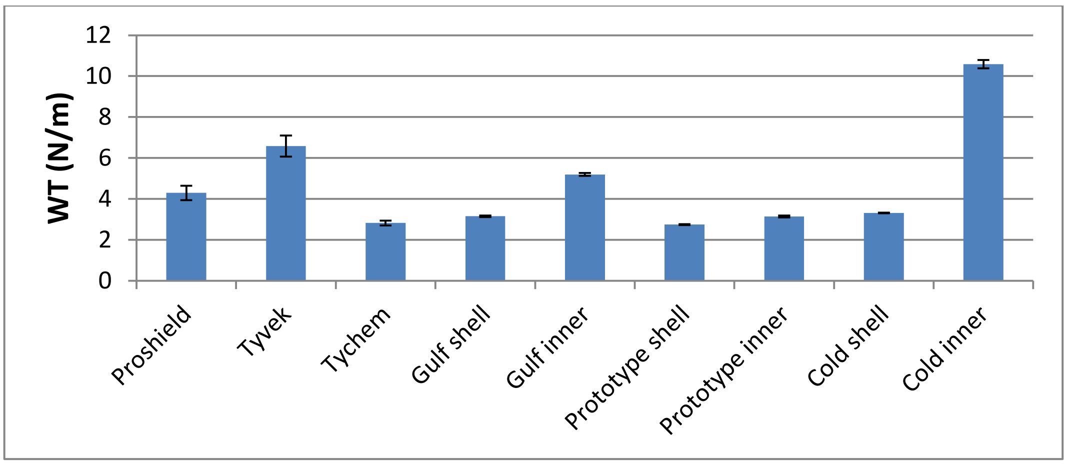
Table 3.4 Water vapour transmission properties measured with DMPC

Fabric	Water Vapour Diffusion Resistance ($s \cdot m^{-1}$)	Water Vapour Flux ($g \cdot m^{-2} \cdot day^{-1}$)	Air Flow Resistance (m^{-1})	Air Permeability ($cm^3\ cm^{-2} \cdot s^{-1}$)
Proshield®	220	6712	4.12×10^{7}	17.0
Tyvek®	394	5636	2.83×10^{9}	0.25
Tychem®	5023	469	1.00×10^{12}	0.0
Gulf	448	2518	3.76×10^{7}	18.6
Prototype	374	5711	4.60×10^{7}	15.2
Cold	878	887	1.25×10^{7}	56.0

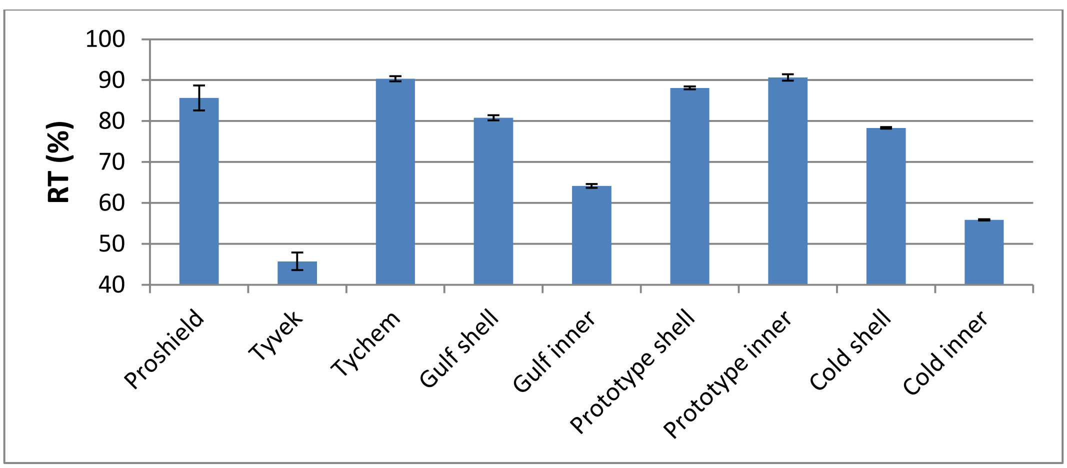
Figure 3.1 Sweating guarded hot plate



a) Tensile linearity (LT)

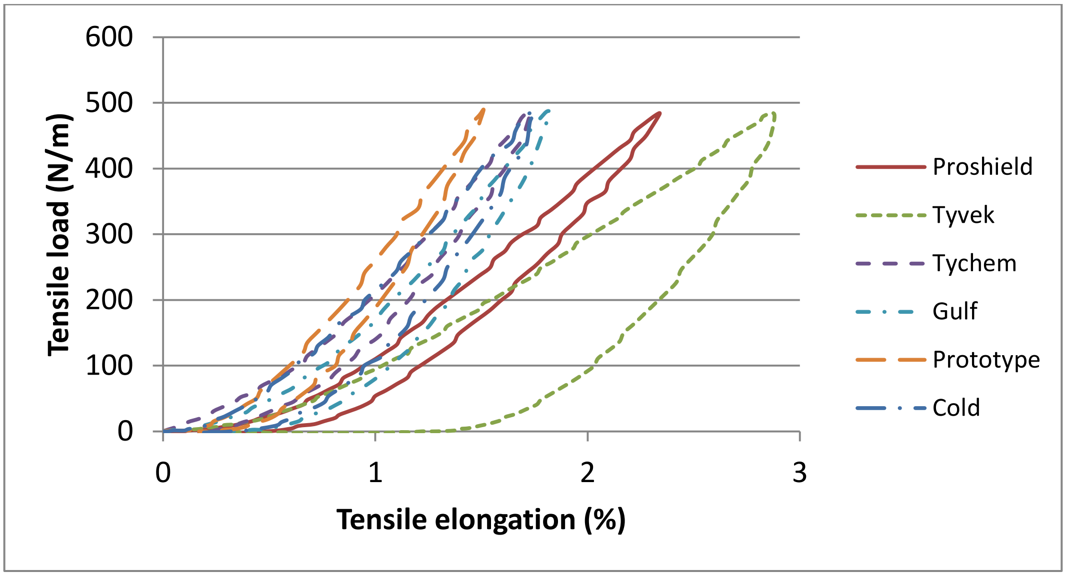


b) Tensile energy per unit area (WT, N/m)



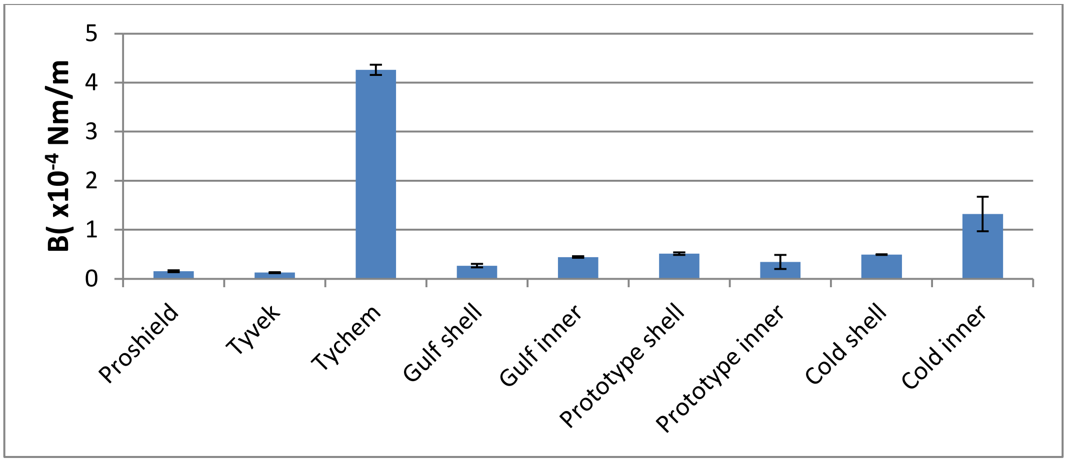
c) Tensile resilience (RT, %)

Figure 3.2 Tensile properties (n=3~5)

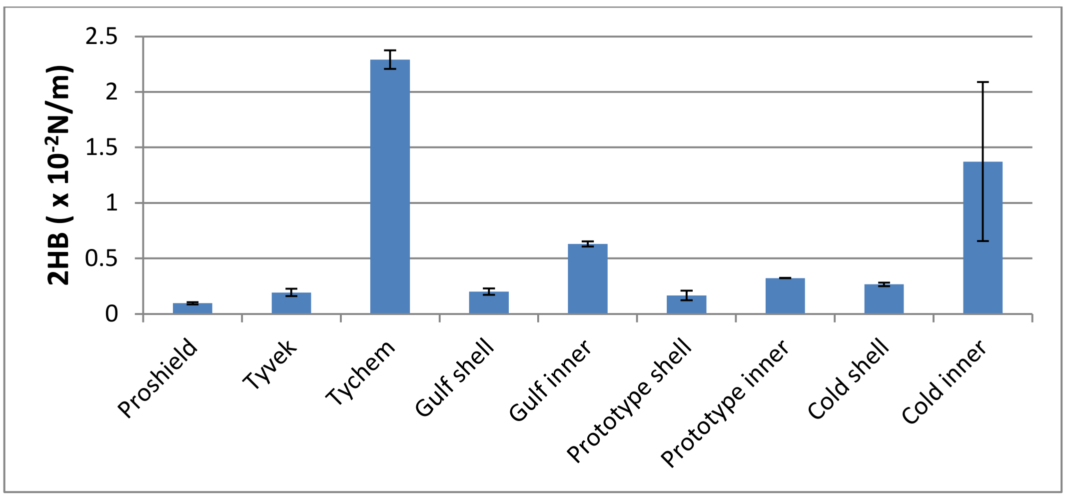


*For multi-layered fabrics Gulf, Prototype, and Cold, the behaviour of shell fabrics are shown.

Figure 3.3 Tensile and recovery behaviour*

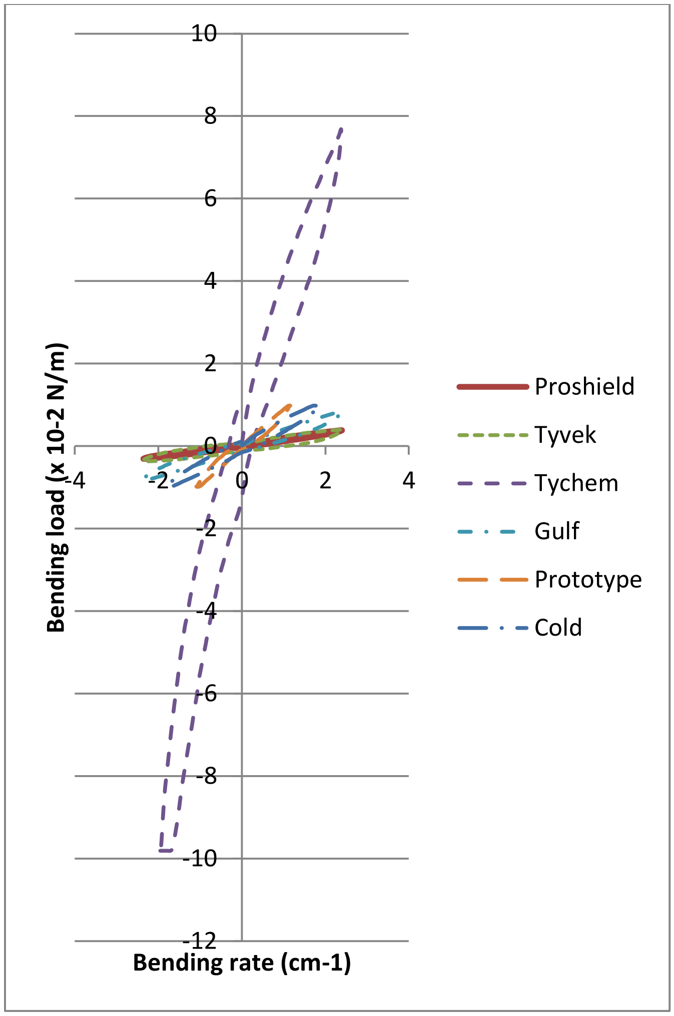


a) B (bending rigidity per unit length, $\times 10^{-4}$ Nm/m)



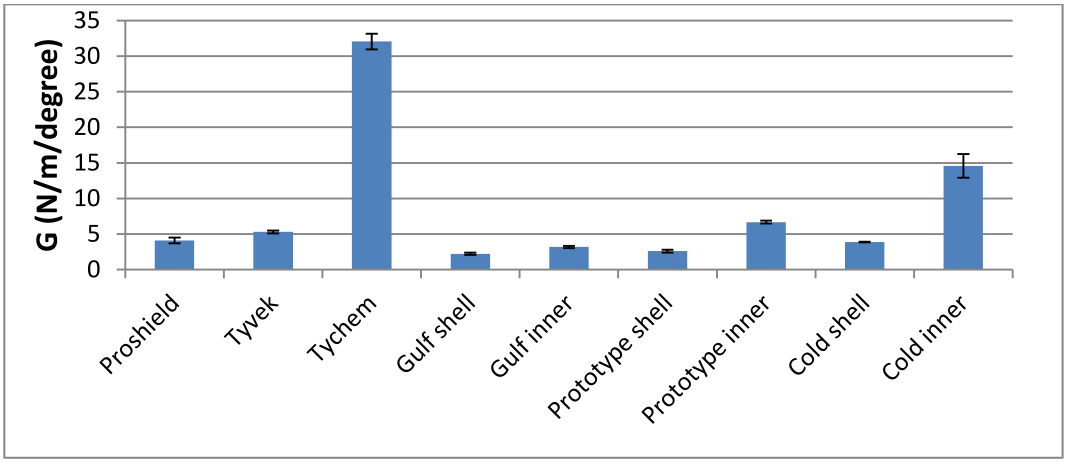
b) 2HB (moment of hysteresis per unit length, $\times 10^{-2}$ N/m)

Figure 3.4 Mean (±SEM) bending properties (n=3~5)

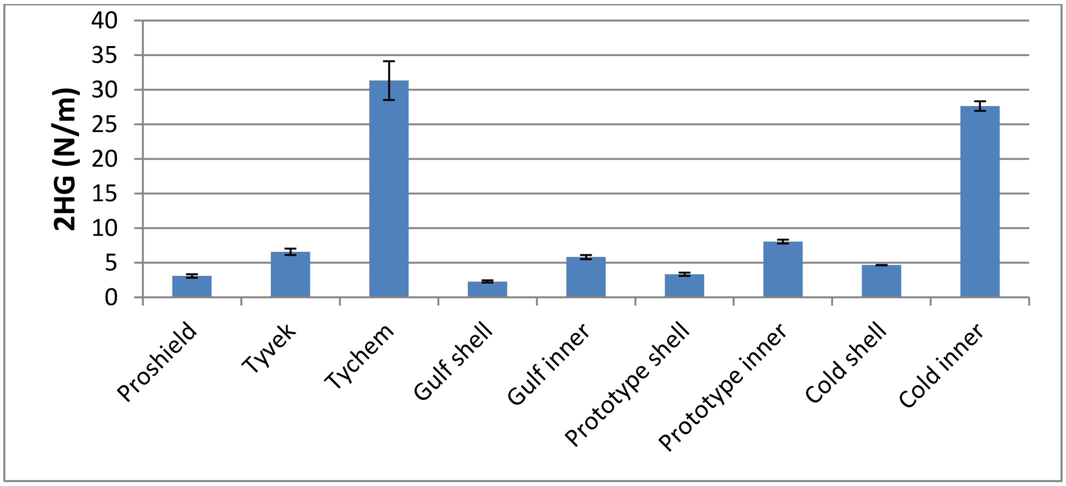


*For multi-layered fabrics Gulf, Prototype, and Cold, the behaviour of shell fabrics are shown.

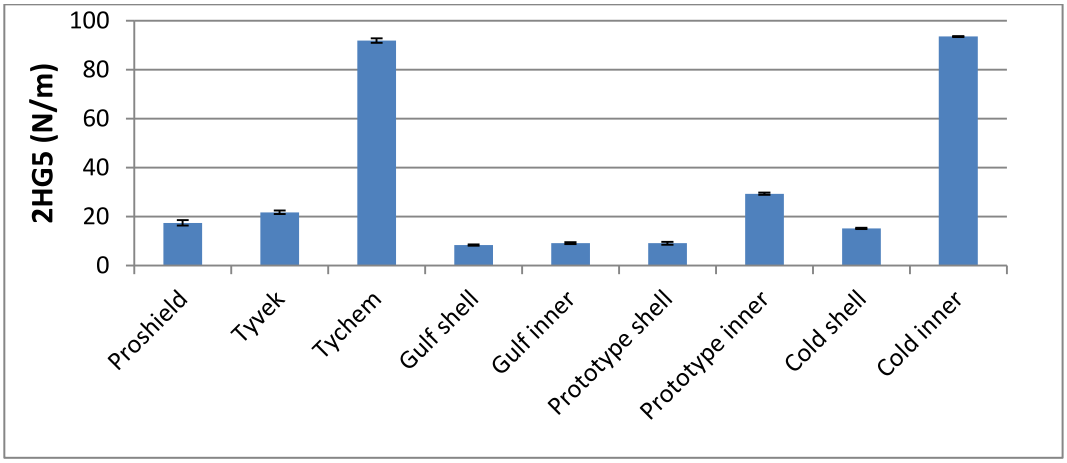
Figure 3.5 Bending and recovery behaviour*



a) Shear stiffness (G, N/m/degree)

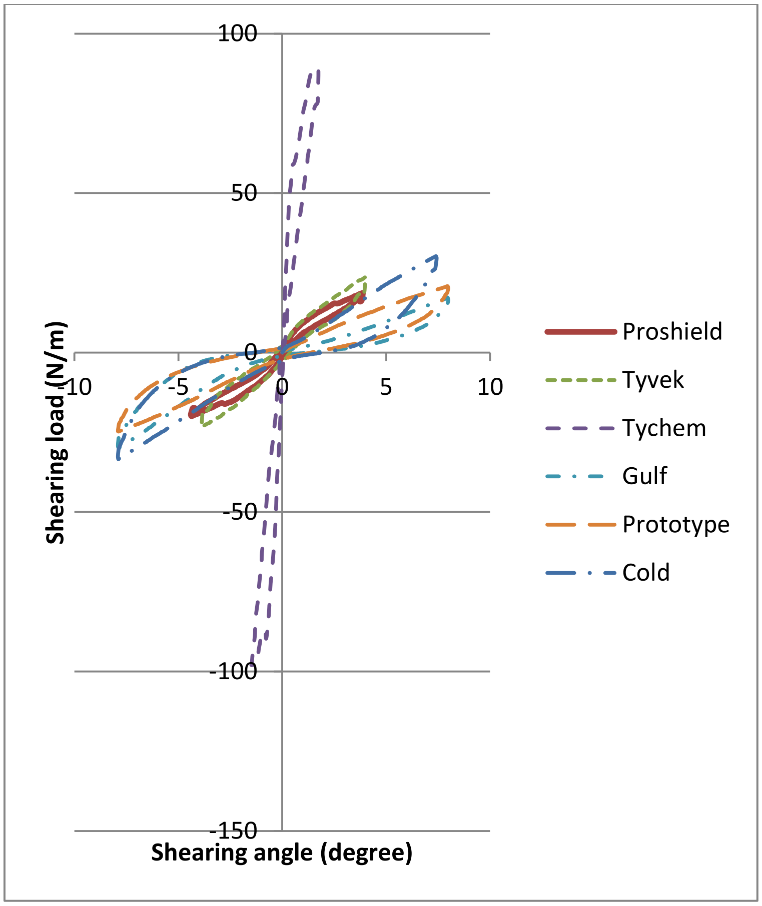


b) Hysteresis at shear angle 0.5 degree (2HG, N/m)



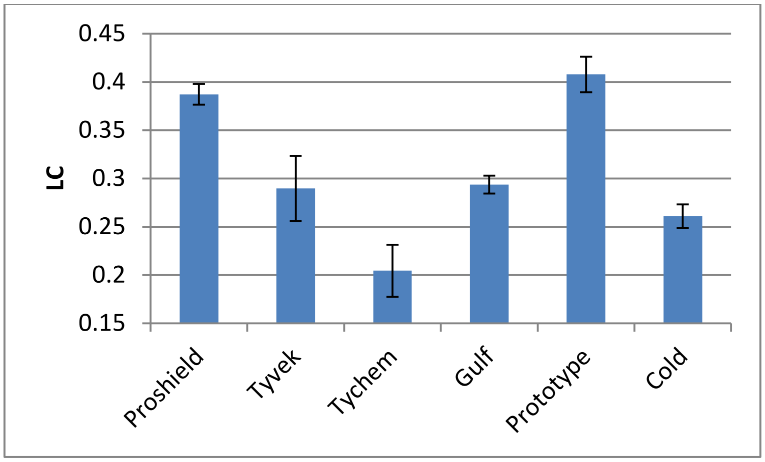
c) Hysteresis at shear angle 5 degree (2HG5, N/m)

Figure 3.6 Shearing properties (n=3~5)

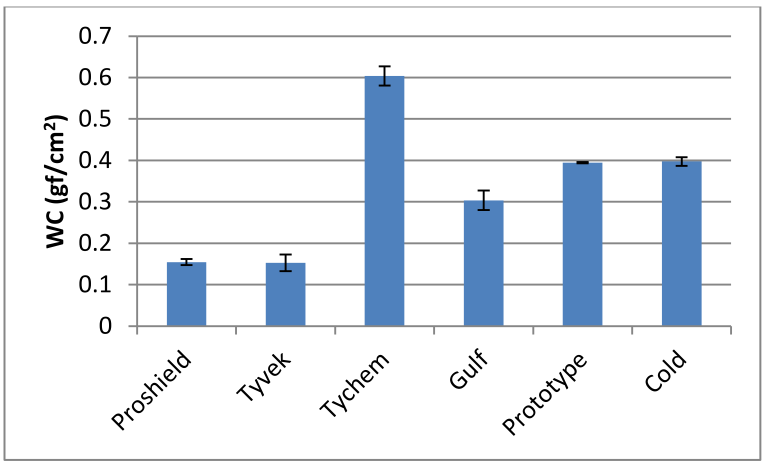


*For multi-layered fabrics Gulf, Prototype, and Cold, the behaviour of shell fabrics are shown.

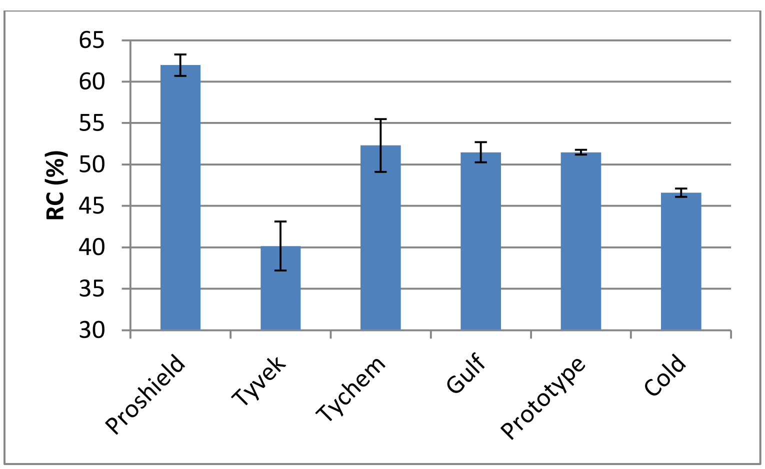
Figure 3.7 Shearing and recovery behaviour



a) Compression linearity (LC)



b) Energy required for compression (WC, gf/cm^2)



c) Compression resilience (RC, %)

Figure 3.8 Compressional properties (n=3~5)

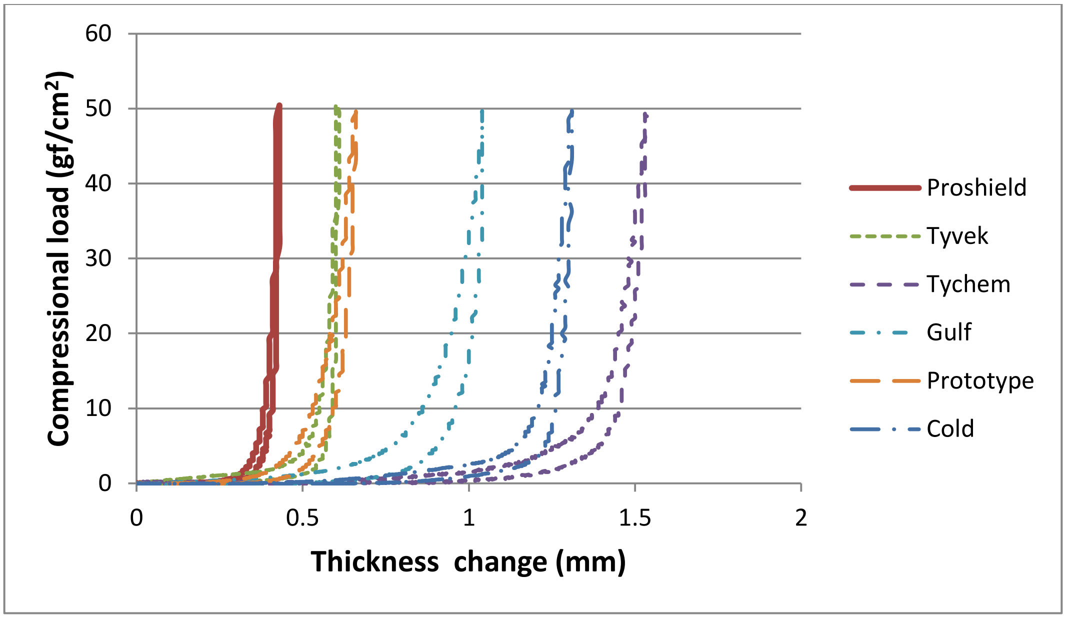


Figure 3.9 Compression and recovery behaviour

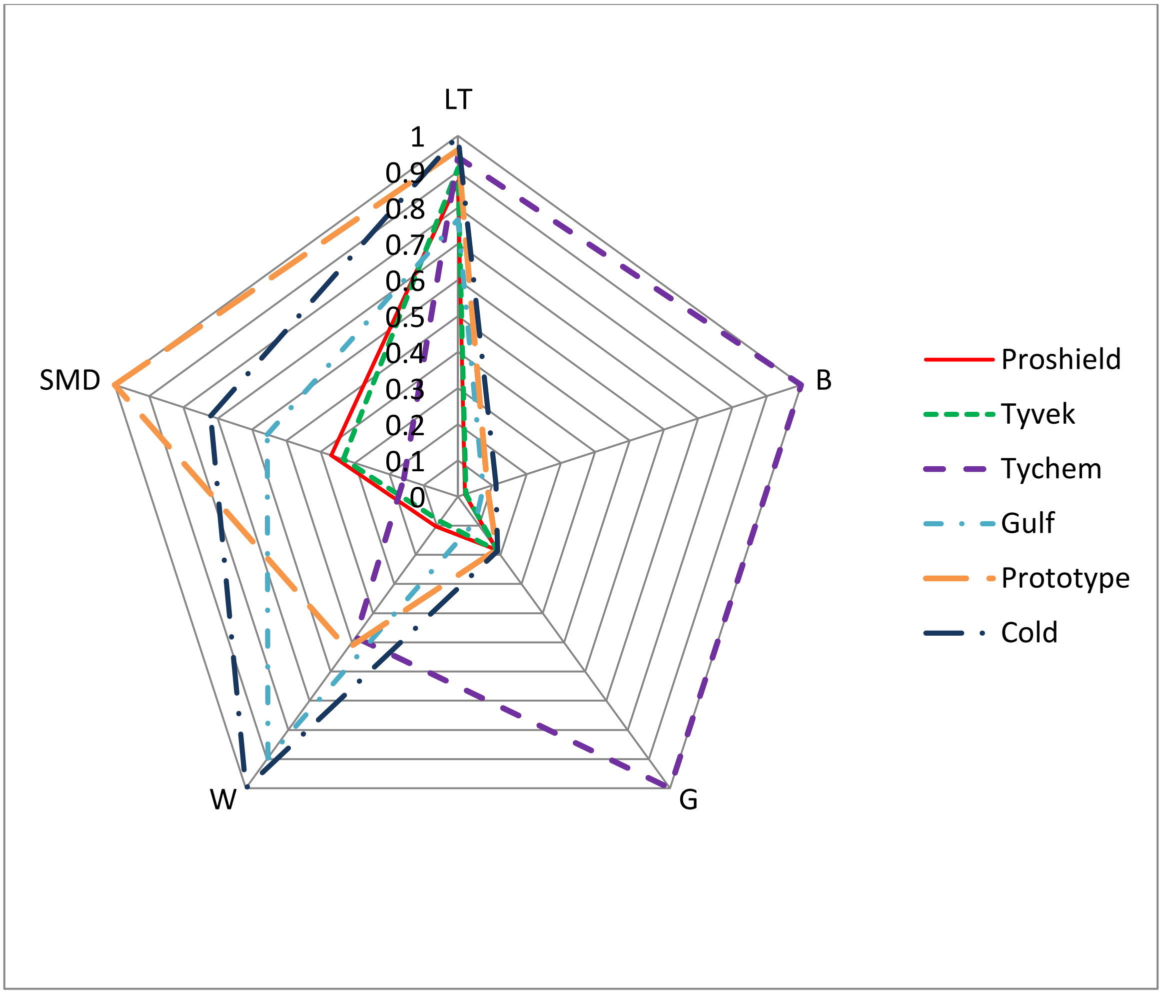
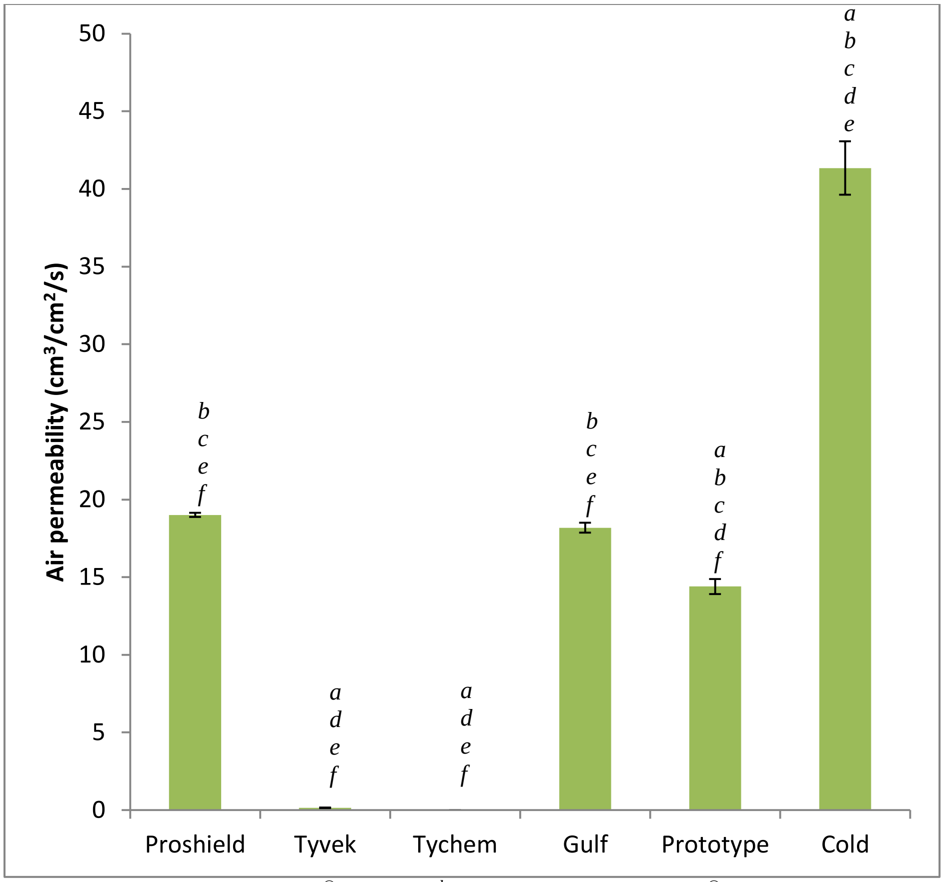
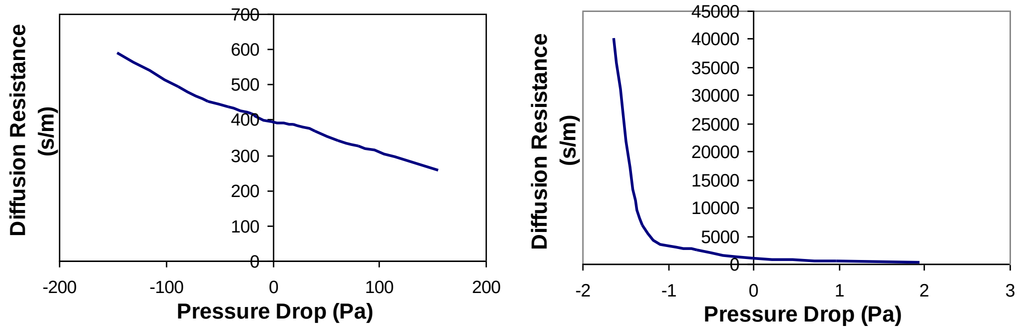


Figure 3.10 Overall physical comfort properties of CPC materials



[a] = different from Proshield®, p<0.05; [b] = different from Tyvek®, p<0.05;
[c] = different from Tychem®, p<0.05; [d] = different from Gulf, p<0.05;
[e] = different from Prototype, p<0.05; [f] = different from Cold, p<0.05;

Figure 3.11 Mean (±SEM) air permeability of different fabric systems (n=10)



a) Fabric Tyvek® b) Fabric Cold

Figure 3.12 Water vapour diffusion resistance across different pressure drops

CHAPTER 4 ERGONOMIC AND COMFORT EVALUATION OF SELECTED CHEMICAL PROTECTIVE CLOVERALLS THROUGH THREE-DIMENSIONAL SCANNING AND THERMAL MANIKIN TESTING

Introduction

In Chapter 3, the thermo-physiological strain and physical burden of wearing CPC were evaluated by analyzing the physical properties of the CPC materials. The bench-scale fabric testing was relatively quick, convenient and economical. The results from these tests were useful for making comparisons among candidate fabrics on the comfort performance related to the evaluated properties. However, the assessment based on material properties does not take into consideration garment features, such as: clothing-covered body surface area, garment openings, and the distribution of textile layers (McCullough, 2005). These features are all related to or in the category of clothing ergonomics, which looks into the relationships between the human body and clothing (Laing & Sleivert, 2002). Clothing ergonomic analysis studies the shape and dimensions of the wearer and the clothing, the relationship between the two systems and the changes to body movement which result from wearing the clothing. (Laing & Sleivert, 2002). Traditional one- or two-dimensional measures of body size and garment size provide only limited information at selected locations, and do not reflect the actual wearing position of a garment on the human body.

In recent years, numerous new technologies and techniques have been introduced to the textile and clothing research area, including three-dimensional (3-D) whole body scanning and thermal sweating manikins. As addressed in Chapter 2, the applications of whole body scanners are rapidly evolving in the textile and clothing research area. In anthropometric research, 3-D scanning has been used to take body measurements (Chen, 2011), to develop made-to-measure patterns (Daanen & Hong, 2008) and to analyze garment fit (Ashdown & Dunne, 2006; Ashdown, Koker, Schoenfelder, & Lyman-Clarke, 2004). Attempts have also been made to quantify air gaps (Kim, Lee, Li, Corner, & Paquette, 2002; Mah & Song, 2010b; Psikuta et al., 2012), contact area (Psikuta et al., 2012), and microclimate volume (Lee et al., 2007; Yu, Wang, Wang, & Li, 2012). Most of the studies on quantification of air gaps and microclimate volume are still very preliminary. They focus on the use of 3-D technology to measure body and garment dimensions, to develop a new protocol of fit evaluation and to visualize and quantify the air gap distribution in three dimensions. In most studies, statistical analyses were not carried out (Kim et al., 2002; Lee et al., 2007; Mah & Song, 2010b; Psikuta et al., 2012).

Thermal sweating manikins are extensively used in estimating the thermal comfort properties of clothing systems, including both heat and moisture transfer properties. As reviewed in Chapter 2, they all have an energy supply system to maintain the manikin at a certain temperature. For the sweating mechanism, some manikins are covered with a cotton knit suit and wetted out with distilled water to create a saturated sweating skin (McCullough et al., 1989). Other manikins have sweat glands on different parts of the body, which sweat continuously (Celcar et al., 2008). On some manikins, the thermal insulation and the evaporative resistance can be determined simultaneously during one test. On other manikins, thermal resistance and evaporative resistance need to be determined in two separate tests (Fan & Qian, 2004; Zuo & McCullough, 2005). Locomotion devices and physiological models have also been incorporated in sweating manikins to investigate thermal regulation more dynamically (Holmer, Gavhed, et al., 1992; Oliveira, Gaspar, & Quintela, 2008; Qian & Fan, 2006a; Wang, 2011). Despite the volume of research being conducted using complex and technologically advanced manikins, the question remains as to whether these manikins provide any more information than the hotplates and whether they are able to replace humans in assessing effects of clothing on human thermal comfort.

The purpose of this portion of the research was to apply 3-D scanning and thermal sweating manikin testing to the determination of clothing ergonomics and heat and moisture transfer properties of the selected CP coveralls. The effects of material type and garment size on these properties are presented and discussed. The results from this study are also compared with the results from bench-scale testing. Further discussion of the relationship of the results from this chapter and the results from the human trials are presented in Chapter 6.

Methods

Experimental design and variables

In this research the independent variables are CPC type and the coverall size. The dependent variables are the full scale air gap size, the volume of the microclimate, the thermal insulation and the evaporative resistance. A two-way factorial experimental design (i.e., four CPC types: Tyvek®, Tychem®, Gulf and Cold; and three sizes: Medium, Large and 2X-large) was carried out to determine the effects of CPC material type and size on the air gap and thermal properties at the garment level.

Materials

Twelve hooded chemical protective (CP) coveralls: 4 materials (Tyvek®, Tychem®, Gulf and Cold) × 3 sizes (Medium, Large and 2X-large) were investigated. The four materials were the same materials described in Chapter 3. Material characteristics and garment design are shown in Table 3.1 and Appendix 1. Proshield® and Prototype were the two types of material which were investigated in Chapter 3 but eliminated from the current study. Multi-layer fabric system Prototype was excluded from this research because it was a material still under development and was only provided in fabric swatches in a limited amount. The permeable nonwoven Proshield® was very different from the other coveralls in terms of the level of protection and area of application. Also, it was available in only one size. Therefore, the Proshield® coverall was not tested in this second study.

Methods

3-D scanning

Three-dimensional scanning was conducted using a Vitus 3-D whole body scanner (Human Solutions GmbH, Germany). A handless male manikin was used in this study. The manikin head and legs cannot move, but the arms can be removed for easier donning and doffing of clothing and have limited rotation at the shoulders. For the scanning process, the manikin was placed within the scanning area in a foot stand which was fixed on a platform (Figure 4.1). The platform was accurately positioned. Both feet were then confirmed fully inserted in the foot stand and reference lines were made (Figure 4.2 a). A plumb-bob was used to mark and align a reference point on the manikin's head (Figure 4.2b). The removable arms were adjusted into position and matching lines were marked on the shoulders and the arms to ensure repeatable positioning (Figure 4.2c). The curtains of the scanner were then closed, the lights in the room turned off, and a scan of the nude manikin made (Figure 4.3a). The manikin was then dressed in a coverall, rubber gloves and splash-proof boot covers and the same alignment preparations performed according to the reference lines and dot marked during the nude scan. A dressed scan was then made (Figure 4.3b). The procedures for the dressed scan were repeated until twelve coveralls were scanned. To ensure packaging folds were removed as much as possible and to be consistent with the other tests, sample coveralls were conditioned according to ASTM D 1776 at 21 ± 1 ºC and 65 ± 2% relative humidity for at least 24 hours prior to scanning and the scan of each coverall was completed within 10 minutes of removal of the coverall from the conditioning room.

3-D scan processing and air gap determination

Geomagic Studio®, an inspection and reverse engineering software for 3-D image processing, was used to transform the 3-D scan data into surface data (Anonymous, 2014b). The mesh editing tool was used to reduce noise, fill holes and remove artifacts and deficiencies in the surface data. The processed 3-D data of the manikin dressed in each coverall was aligned with the processed nude data using Geomagic Qualify® software using the uncovered body parts as the reference shapes (Anonymous, 2014a). Comparisons between the nude and the dressed models and calculations of air gaps and volumes were made using the same software.

The average air gap size (AAGS) was defined as the average distance between points on the surface of the nude and dressed manikin. Appendix 3 gives a cross-sectional view of a 3-D deviation spectrum, which describes how the analysis was performed. To visualize the overall air gap distribution, a front and a back view of the deviation spectrum of each pair of scans were generated. The different sizes of air gaps were shown with different colours on a map (Appendix 4). The volumes of microclimate (V_m) were determined by running a volume deviation between the dressed manikin and the nude manikin. As for the calculation of the AAGS and the V_m, the thickness of the fabric was not subtracted from the measurements. For single layer fabrics, Tyvek® and Tychem®, the thickness values are very small compare to the size of the air gap (Lee et al., 2007; Mah & Song, 2010b; Psikuta et al., 2012). For the thicker multi-layer fabrics, Gulf and Cold, the configuration of the inner layers of the coveralls when dressed on the manikin is not known. Secondly, for the discussion of thermal properties and ergonomics, it is reasonable to consider all of the spaces beneath the shell fabric as the microclimate (Kim & Hong, 2006; Oliveira et al., 2011). For the purpose of making comparison among coveralls, the following regions were excluded from the calculation of the air gap size and microclimate volume: 1) neck and head; 2) forearms and 3) calves and feet. These areas were cut from the data to avoid complexity of the regions which contain multiple layers and different materials (rubber gloves and nonwoven splash-proof boot covers) from the CPC materials, and the regions with garment openings (face, hands and feet openings). Horizontal planes at neck, elbow and knee were positioned at the same levels on the vertical axis of the nude scan to ensure the regions being cut in each aligned scan were identical-sized body parts.

Sweating manikin test

The thermal insulation of clothing, R_{ct-c} and the evaporative resistance of clothing, R_{et-c} were measured using a thermal sweating manikin Newton (SGS, Hong Kong). The R_{ct-c} was measured under the environmental conditions of -10 ºC, <10% relative humidity, and air velocity at 0.4 m/s according to ASTM F 1291 (American Society for Testing and Materials, 2005a). The air temperature at -10 ºC was selected because the multi-layered ensembles had high thermal insulation values. According to the standard, the air temperature should be lowered “so that a minimum heat flux of 20 W/m^2 from the manikin’s segments is maintained” (American Society for Testing and Materials, 2005a). The nude manikin was tested for the insulation provided by the air layer surrounding the nude manikin in the same environmental conditions at the beginning of all the tests. The R_{et-c} tests were conducted under the environmental conditions of 35ºC, 40% relative humidity, and air velocity at 0.4 m/s according to ASTM F 2370 (American Society for Testing and Materials, 2005b). The nude manikin was tested at the beginning of each test in the same environmental conditions to determine the evaporative resistance provided by the air layer around the nude manikin. In each test, the manikin was dressed with socks, athletic shoes, rubber gloves, splash-proof boot covers and the CP coverall (Figure 4.4).

Statistical analysis

Descriptive statistics including the mean (M), standard deviation (SD), coefficient of variation in percent (CV%), and ranges (minimum and maximum values) were determined for data on the average air gap size (AAGS), volume of microclimate (V_m), R_{ct-c} and R_{et-c} using SPSS (version 21.0). One-way ANOVA was used to compare the AAGS, V_m, R_{ct-c} and R_{et-c} of different garment types and garment sizes. For all tests a significance level of $p \leq 0.05$ was used. Where significant effects or interactions were found, post-hoc comparisons using the Tukey HSD test were made to locate significant differences.

Results and Discussion

Size of air gaps

The mean values (±SEM) of AAGS for different coverall types are displayed in Figure 4.5. The one-way ANOVA for the effect of fabric type on AAGS is shown in Table 4.1. There was a trend showing that within the same group (i.e., single-layer nonwoven or multi-layer composite), the stiffer materials, Tychem® and Cold had larger AAGS (at 39.1 and 39.3 mm) than the more flexible materials, Tyvek® and Gulf (25.6 and 27.3 mm). However, the differences were not significant at $p \leq 0.05$ ($p = 0.066$) possibly due to the small sample size. This trend was consistent with findings from previous studies (Mah & Song, 2010a). A stiffer fabric suggests less drape when the garment is worn hence larger overall distances from the body surface to the clothing surface (Mah & Song, 2010a).

The mean values (±SEM) of AAGS for different sizes of coveralls are displayed in Figure 4.6. One-way ANOVA was carried out to determine the effect of size on AAGS. No significant difference was found at $p \leq 0.05$ (Table 4.2). Overall, the larger the size, the bigger the AAGS. When looking at the changes in AAGS from Medium to Large (Figure 4.7), the changes for all four types of coveralls were roughly similar, in the range of 4.0 mm to 6.8 mm. However, when 2X-large was compared with Large, the fabrics with lower unit mass, Tyvek® and Tychem® still showed relatively large increase in AAGS (7.7 mm and 15.0 mm). The heavy fabrics, Gulf and Cold, had relatively small increase in AAGS when the size was increased from Large to 2X-large (0.6 mm and 2.6 mm). This was a result of combined effects from fabric mechanical properties, unit mass and drape characteristics.

Air gap size is an important parameter in ergonomic analysis of protective clothing. It is a full-scale indicator of the two interdependent factors: ease and bulkiness. Only garments with suitable air gap size and distribution, which means the garment is neither too tight nor too loose, can be regarded as ergonomically comfortable. A smaller AAGS suggests a tighter fit (less ease) and less bulk in the CP coveralls. With the consideration of allowing the worker to move uninhibited, protective coveralls are usually designed to have sufficient ease (Huck et al., 1997). According to the size chart of Tyvek® and Tychem® coveralls (Appendix 5), the smallest coverall size in this study, Medium, was recommended for the height range 5 feet 3 inches to 5 feet 8 inches. The size was selected to be under-sized for the manikin, whose height is 5 feet 11 inches. It was found that these undersized coveralls still provided considerably sufficient ease (AAGS > 11 mm). As mentioned already, it is relatively rare to find protective clothing with too little ease. Conversely, it is more commonly seen in work environments that a garment is too large, hence wearer mobility is adversely affected by the extra ease and bulkiness (Adams & Keyserling, 1996). Based on the AAGS results obtained through 3-D scanning, Tychem® and Cold are more likely to restrict movements than Tyvek® and Gulf in the same size due to the extra bulkiness provided. The restriction to movements in Tychem® and Cold will be further aggravated when an oversized coverall is worn.

Appendix 6 gives the detailed AAGS and V_m for each coveralls.

Volume of microclimate

The mean values (±SEM) of V_m for different coverall types are displayed in Figure 4.8. The one-way ANOVA for the effect of fabric type on V_m is shown in Table 4.3. Similar to the results of AAGS, the stiffer materials, Tychem® and Cold had larger V_m (at 5.09×10^7 and 5.22×10^7 mm^3) than the more flexible materials, Tyvek® and Gulf (3.24×10^7 and 3.50×10^7 mm^3) respectively. The ANOVA results show that the differences were not significant at $p \leq 0.05$ ($p = 0.056$). The mean values (±SEM) of V_m for different sizes of coveralls are displayed in Figure 4.9. One-way ANOVA was carried out to determine the effect of size on V_m. It was noted that garment size did not contribute to a significant difference in V_m at $p \leq 0.05$ (Table 4.4). The general trend was the V_m increases with the increase in size.

Air volume of the microclimate, highly related to the AAGS, is not only an important factor related to wearer mobility, but also a crucial factor for the determination of thermal insulation of clothing ensembles (McCullough & Hong, 1994). Air trapped in the microclimate may enhance or reduce the thermal insulation of the garment system. Still air has a lower thermal conductivity than fibres. When the air space is under a certain limit, the still air contributes to the thermal insulation of the clothing ensemble. But once the air space in the microclimate reaches the limit, the thermal insulation value of the clothing may start to decrease due to the convection heat loss from the body surface (Lee et al., 2007; McCullough & Hong, 1994). In a previous study conducted by Lee et al. (2007), a cooling effect due to active convection was observed as the air volume of the upper torso exceeded 7×10^3 cm^3. In some other earlier studies, the maximum thickness of a still air layer was estimated at 12 to 18 mm (Lotens & Havenith, 1991; Yoo et al., 2000). Among all the coveralls scanned, the smallest V_m and AAGS were found with Medium Tyvek®, at 23.2×10^3 cm^3 and 18.6 mm, which were believed to have exceeded the limit for convective heat transfer. Therefore, the air space of the microclimate of these CP coveralls is unlikely to act as an extra barrier, preventing heat transfer from the body to the environment.

Thermal insulation of clothing ($R_{ct\text{-}c}$)

The mean values (±SEM) of $R_{ct\text{-}c}$ for the four fabrics are depicted in Figure 4.10. The one-way ANOVA analyzing the effect of fabric type on $R_{ct\text{-}c}$ is shown in Table 4.5. The level of $R_{ct\text{-}c}$ ranged from 0.187 m^2K/W to 0.262 m^2 K/W (Figure 4.10). The effect of material type was highly significant on influencing $R_{ct\text{-}c}$ ($F_{3,8} = 172.4$, $p \leq 0.01$). The Tukey's post hoc test results show that the $R_{ct\text{-}c}$ of the multi-layered Gulf and Cold are significantly higher than Tyvek® and Tychem®. The mean values (±SEM) of $R_{ct\text{-}c}$ for three different garment sizes are displayed in Figure 4.11. The one-way ANOVA examining the effect of garment size on $R_{ct\text{-}c}$ is shown in Table 4.7. It was found that garment size did not contribute to a significant difference in $R_{ct\text{-}c}$ ($F_{2,9}=0.014$, NS) (Table 4.7).

In Chapter 3, the bench-scale thermal insulation, R_{ct} was found to be correlated to the material thickness, r = 0.883 ($p \leq 0.01$). In this study, thermal insulation of clothing, R_{ct-c} was still found to be dependent on material thickness. The Pearson correlation coefficient between R_{ct-c} and material thickness (Table 3.1) equals to 0.848 ($p \leq 0.01$), indicating that clothing thermal insulation increases as the thickness of the garment layers increases. Overall, the results from the thermal manikin tests (R_{ct-c}) agreed with the results from hot plate tests (R_{ct}) in the ranking of Tyvek® - Tychem® - Gulf - Cold, from the lowest to the highest thermal insulation. The R_{ct-c} was found to have a positive linear relationship with R_{ct}, $R^2 = 0.389$ ($p \leq 0.05$). Fabric R_{ct} explains 38.9% of the variance in full-scale R_{ct-c}. The rest of the variance in R_{ct-c} can be explained by garment features and whole body heat exchange related variables, such as three-dimensional effects, layer effects, drape, design details (zipper or Velcro closing, belt or elastic at waist) (Holmer & Nilsson, 1995; McCullough, 2005). Another finding was the R_{ct-c} did not change significantly when the garment size changed. As addressed above, this is due to the fact that V_m of these garments had already exceeded the critical air gap size at which convection is initiated. In common work places, a low clothing insulation is usually desirable to promote heat dissipation; therefore thinner materials should be preferred in the construction of CPC. Garment size is not a crucial factor for thermal comfort. Undersized or oversized coverall may cause reduced wear mobility, however, it was not an influencing parameter for the thermal comfort of the CP coveralls investigated in this study.

Evaporative resistance of clothing (R_{et-c})

In Figure 4.12, the mean values (±SEM) of R_{et-c} for the coveralls made of four different fabrics are shown. The R_{et-c} for Gulf, Tyvek® and Cold were 34.3, 39.9 and 52.8 $m^2 \cdot kPa/W$, respectively. The mean R_{et-c} for Tychem® was extremely high at 334.7 $m^2 \cdot kPa/W$. The one-way ANOVA results analyzing the effect of fabric type on R_{et-c} are listed in Table 4.8. The fabric type significantly influenced the R_{et-c} ($F_{3,8} = 1287.0$, $p \leq 0.001$). The Tukey's post hoc test results (Table 4.9) show that the R_{et-c} of Tychem® was the highest. The heaviest fabric, Cold has the second highest R_{et-c}, which is significantly higher than Gulf but not significantly different from Tyvek®. The lowest R_{et-c} was found with Gulf and Tyvek® and they are not significantly different from each other. Similar to the effects of garment size on R_{ct-c}, garment size had no significant effect on R_{et-c}. The mean values (±SEM) of R_{et-c} for three different garment sizes and the one-way ANOVA results are displayed in Figure 4.13 and Table 4.10. Appendix 7 lists the R_{ct-c} and R_{et-c} values from each individual test.

The R_{et-c} tests were performed under the isothermal conditions, where the air temperature was the same as the manikin's surface temperature at 35°C. There was no dry heat exchange occurring between the manikin and the environment during these tests (American Society for Testing and Materials, 2005b). The full-scale R_{et-c} was found to be highly correlated to the bench scale R_{et} from the sweating guarded hotplate testing, $R^2 = 0.970$, $p \leq 0.01$. This means as high as 97.0% of variance in clothing evaporative resistance can be explained by the fabric evaporative resistance. The number was surprisingly high as the sweating guarded hotplate was considered as a "flat" apparatus which does not take into account the garment features such as body coverage, human body shape and clothing microclimate (Wang, Gao, Kuklane, & Holmer, 2011). Greater differences were expected between the evaporative resistance values determined on the sweating guarded hotplate and on the sweating manikin. One possible explanation for the similar results is the body coverage by all the garment types was strictly controlled in this study. All garments were hooded coveralls of similar design. Gloves and boot covers were also used to cover the hands and feet and to seal the openings on the sleeves and pants. The only uncovered body part was the face, where one sensor (out of 34) was located. In addition, elastic at the face opening meant ventilation through garment openings was minimal. Also convection could not take place due to the isothermal condition. Therefore, the moisture transfer in the clothing system was not significantly changed by exposed skin area, ventilation or convection. In real wearing situations, when the ambient temperature is lower than 35°C and workers are moving, there would be active convection and ventilation which helps the transfer of moisture.

Summary and Limitations

Ergonomic analysis was made for twelve CP coveralls using 3-D body scanning. No significant effects due to garment size or clothing type were discovered on AAGS and V_m. The general trend suggested that AAGS was larger with stiffer materials. The full-scale R_{ct-c} and R_{et-c} were determined using a thermal sweating manikin. The results were analyzed and compared to the results from the sweating guarded hotplate tests. General agreement was found between the results from bench-scale and full-scale testing. Garment size was not an influential factor for heat and moisture transfer through the garment system.

Limitations of this study include:

- The post-processing procedure on the 3-D data using Geomagic software was challenging due to complexity of 3-D forms counterbalanced by available computing power. Furthermore, a high precision aligning of the 3-D scans despite the surface deficiencies was very demanding. Consequently, the majority of manipulation of the 3-D scans had to be done manually which was very time consuming. As an advanced tool for garment ergonomic analysis, 3-D scanning provides comprehensive information on the shape and dimensions of the body and the garment. However, due to the irregularity of the images, the data processing was complicated and time consuming.
- Due to the availability of the thermal sweating manikin and the limitations using Geomagic software, only one replication was tested per garment type per size.
- In this study, body coverage and body position were controlled, so that the thermal insulation and evaporative resistance of the whole garment system could be evaluated to show the effects of fabric type and size on the whole-body heat and moisture transfer. The control in the research design was necessary because the results from this study were to be compared with the results from the human trials (Chapter 5). However, it may be too excessive to show the advantages of running tests at full-scale. On the other hand, this also suggested that when comparisons on heat and moisture transfer are made between two garments with similar design and construction, a stationary thermal sweating manikin may not necessarily provide more information than the sweating guarded hotplate.

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Table 4.1 Fabric type affecting AAGS - ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	488.434	3	162.811	3.580	.066
Within Groups	363.855	8	45.482		
Total	852.289	11			

Table 4.2 Garment size affecting AAGS - ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	286.571	2	143.285	2.280	.158
Within Groups	565.718	9	62.858		
Total	852.289	11			

Table 4.3 Fabric type affecting V_m - ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	9.69×10^{14}	3	3.23×10^{14}	3.865	.056
Within Groups	6.69×10^{14}	8	0.84×10^{14}		
Total	16.38×10^{14}	11			

Table 4.4 Garment size affecting V_m - ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	5.44×10^{14}	2	2.72×10^{14}	2.240	.162
Within Groups	10.94×10^{14}	9	1.22×10^{14}		
Total	16.38×10^{14}	11			

Table 4.5 Fabric type affecting R_{ct-c} - ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	.014	3	.005	172.407	.000
Within Groups	.000	8	.000		
Total	.015	11			

Table 4.6 Differences in R_{ct-c} for fabric types - Tukey's range test

Interactions	Mean	n	Tukey's groupings
CPC Type			
Tyvek®	0.187	3	A
Tychem®	0.190	3	A
Gulf	0.253	3	B
Cold	0.262	3	B

Means grouped by lines are not significantly different at $p \leq 0.05$

Table 4.7 Garment size affecting R_{ct-c} - ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	.000	2	.000	.014	.986
Within Groups	.015	9	.002		
Total	.015	11			

Table 4.8 Fabric type affecting R_{et-c} - ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	192868.709	3	64289.570	1287.036	.000
Within Groups	399.613	8	49.952		
Total	193268.322	11			

Table 4.9 Differences in R_{et-c} for coverall types - Tukey's range test

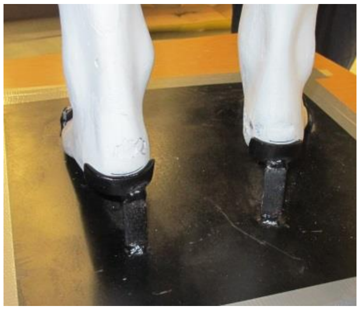
Interactions	Mean	n	Tukey's groupings
CPC Type			
Gulf	34.3	3	
Tyvek®	39.9	3	
Cold	52.8	3	
Tychem®	334.7	3	

Means grouped by lines are not significantly different at $p \leq 0.05$

Table 4.10 Garment size affecting R_{et-c} - ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	24.815	2	12.408	.001	.999
Within Groups	193243.508	9	21471.501		
Total	193268.323	11			

Figure 4.1 Male manikin for scan



a) securing in foot stand

b) plumb-bob positioning

c) shoulder and arm matching

Figure 4.2 Nude manikin scanning

a) nude b) dressed

Figure 4.3 Manikin scans

Figure 4.4 Sweating manikin tests in Tyvek®, Tychem®, Gulf and Cold

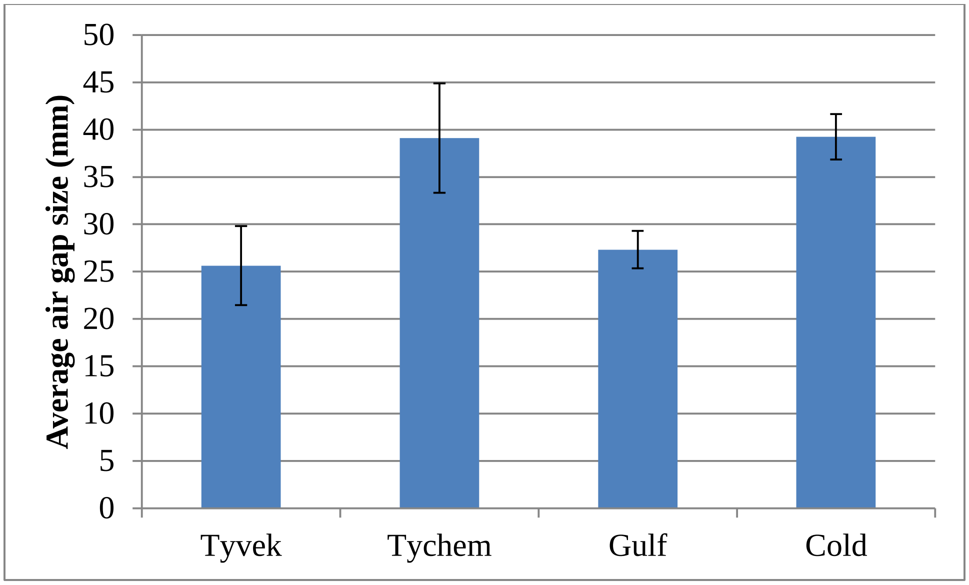


Figure 4.5 Means (±SEM) of AAGS of four types of chemical protective coveralls

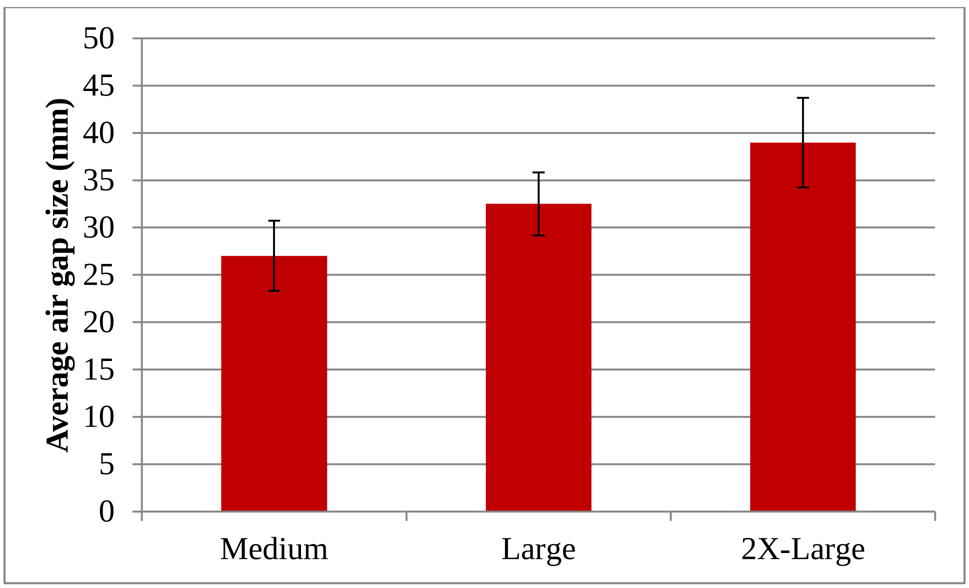


Figure 4.6 Means (±SEM) of AAGS of three sizes of chemical protective coveralls

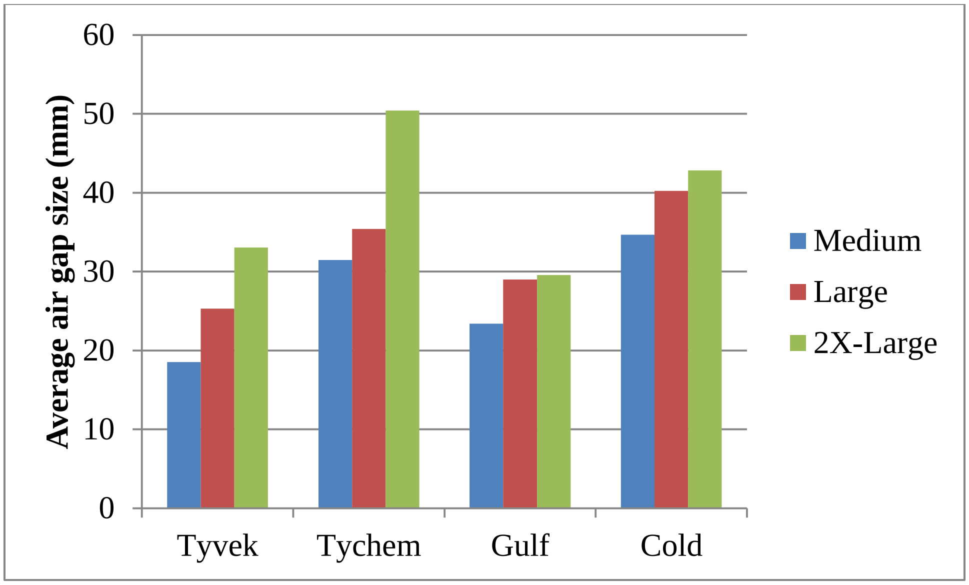


Figure 4.7 AAGS of twelve chemical protective coveralls

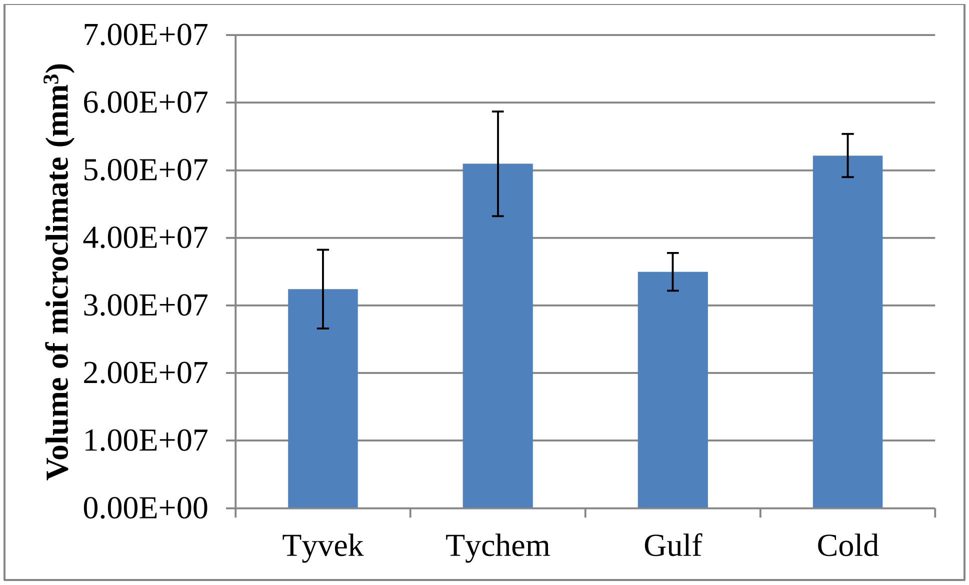


Figure 4.8 Means (±SEM) of V_m of four types of chemical protective coveralls

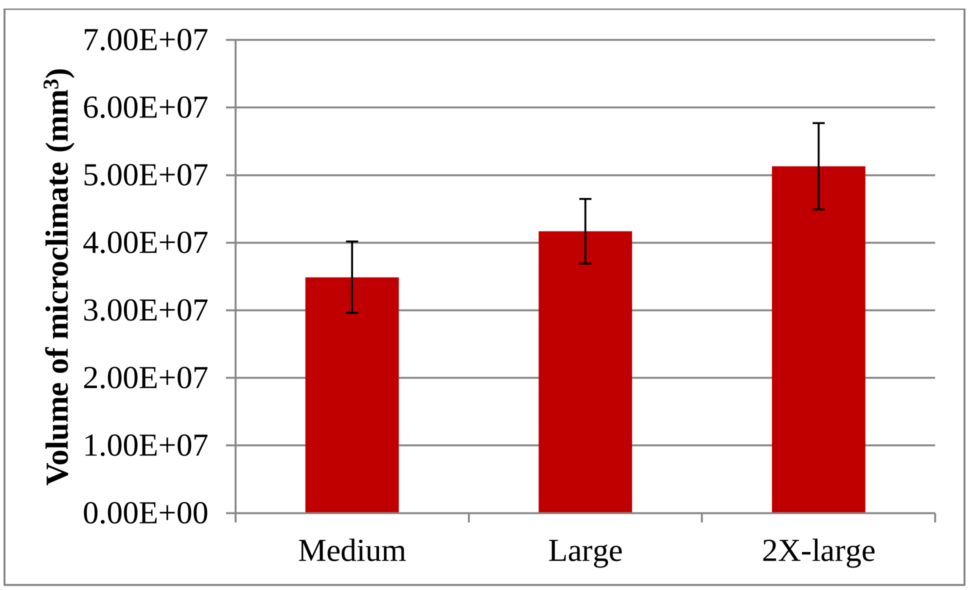


Figure 4.9 Means (±SEM) of V_m of three sizes of chemical protective coveralls

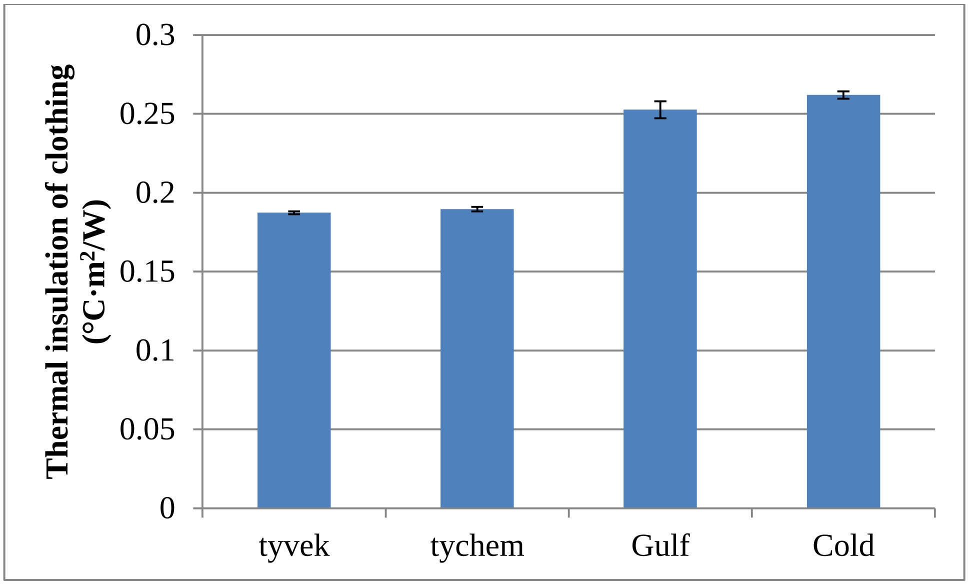


Figure 4.10 Means (±SEM) of $R_{ct\text{-}c}$ of four types of chemical protective coveralls

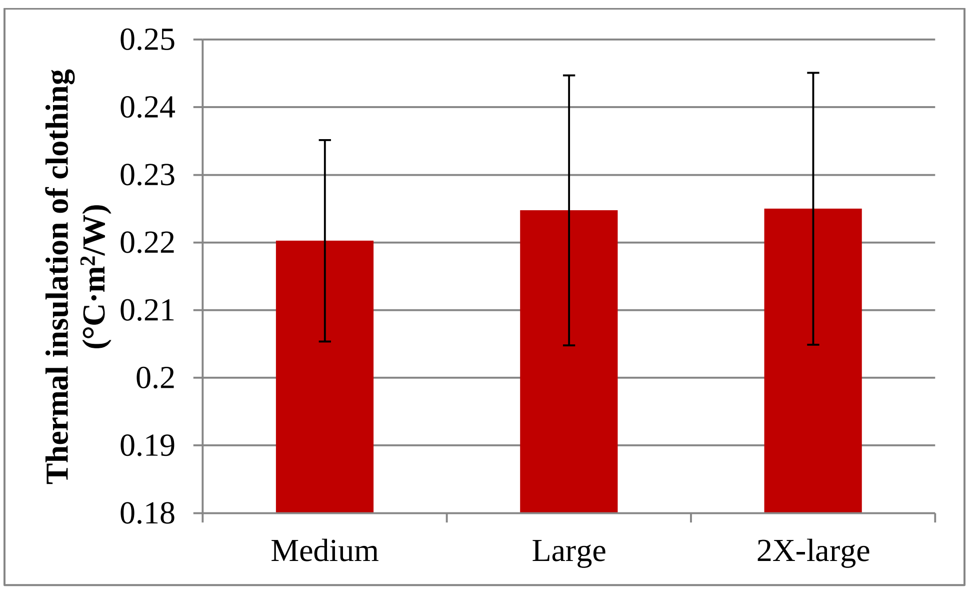


Figure 4.11 Means (±SEM) of $R_{ct\text{-}c}$ of three sizes of chemical protective coveralls

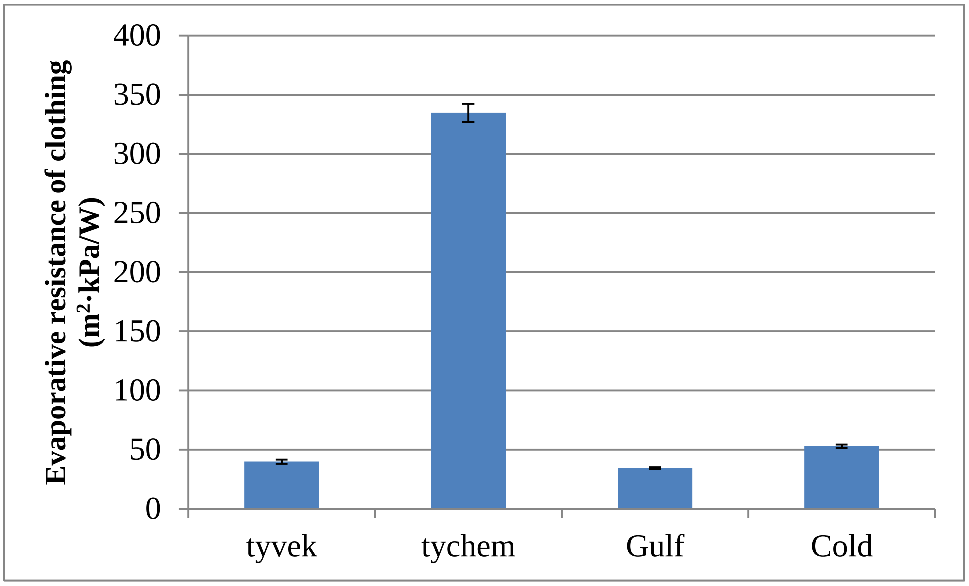


Figure 4.12 Means (±SEM) of R_{et-c} of four types of chemical protective coveralls

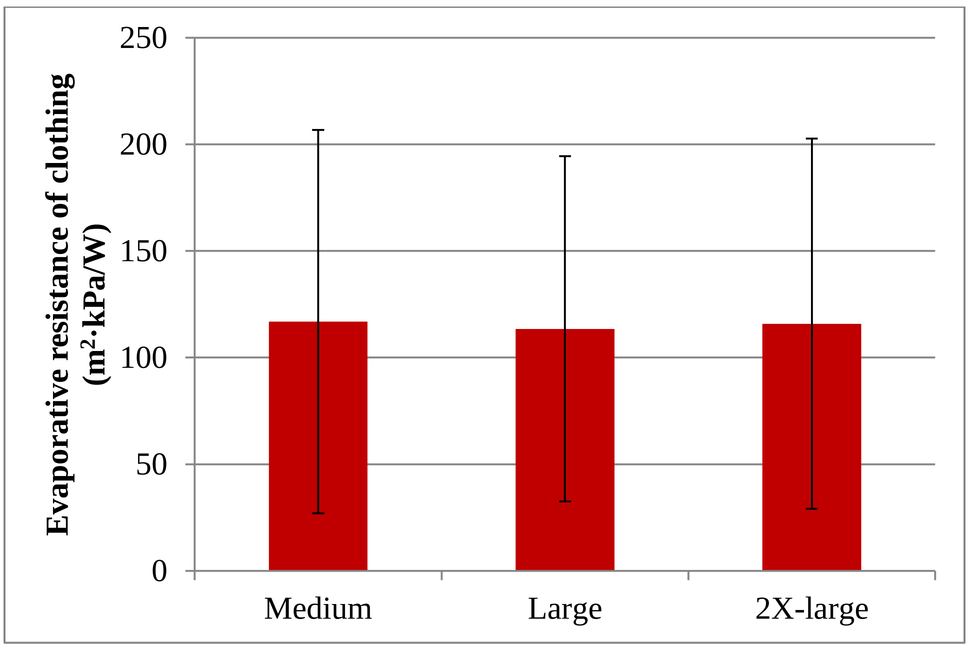


Figure 4.13 Means (±SEM) of R_{et-c} of three sizes of chemical protective coveralls

CHAPTER 5 WEAR TRIAL INVESTIGATION OF THERMO-PHYSIOLOGICAL STRAIN AND PHYSICAL BURDEN DURING EXERCISE WITH SELECTED CHEMICAL PROTECTIVE COVERALLS

Introduction

Chemical protective clothing (CPC) is worn in a variety of circumstances to protect workers from the effects of chemical and biological substances (Raheel, 1994). Wearing CPC may disrupt thermal balance by increasing heat production and preventing heat dissipation. It has been found that wearing protective clothing significantly increases metabolic rate and leads to heat storage during different exercise intensities and under various environments (Dorman & Havenith, 2009; Levine et al., 2001; Selkirk & McLellan, 2004). Work performance and thermal comfort can be impaired due to the extra weight, increased thickness, thermal insulation and bulkiness of the CPC (Duncan et al., 2011; Endrusick et al., 2005; York & Grey, 1986). In cases where impermeable encapsulated ensembles are used, evaporative heat transfer is prevented. Consequently, the heat loss required to maintain a thermal steady state cannot take place (Bishop, Smith, Ray, Beaird, & Smith, 1994; Veghte, 1989). This is especially true when a person is working intensely or in a hot environment, creating a condition of uncompensable heat stress (Cheung, McLellan, & Tenaglia, 2000; Selkirk & McLellan, 2004). In addition, CPC systems are expected to impair physical comfort and increase restrictions to movement because of their heavy, stiff, inflexible and bulky nature (Ashdown, 2011; Huck, 1988; Wen, Song, & Duncan, 2012).

The protection vs. comfort dilemma has always been a challenge in the design and construction of protective clothing. Protection is achieved by isolating humans from the hazardous environment. Impermeable barriers and absorbent layers in clothing are the two commonly used mechanisms of isolation for chemical and biological protection (Slater, 1996). Fabric and garment properties that have been integrated to improve protection, such as greater thickness, impermeability and encapsulation, negatively affect wearing comfort in different ways (Rossi, 2005). Extra weight, bulkiness and higher thermal insulation are direct results of increased thickness. Added weight and bulkiness result in extra energy cost and restrictions to movement when working in the garment (Adams & Keyserling, 1995; Rissanen et al., 2008). Higher thermal insulation means less heat loss through the garment system. Impermeability and enclosure greatly impair evaporative heat transfer from the clothing system (Lee & Obendorf, 2007; Shalev et al., 1996). Furthermore, impermeability is usually accompanied by stiffness and inflexibility, which bring additional restrictions to movement. Thus, there is a trade-off between the quality of protection and comfort and work performance. The design of any protective clothing is the result of a compromise between the two factors.

Laboratory testing of textile properties have been widely used to evaluate clothing comfort. Bench-scale testing of thickness, mass per unit area, air permeability, thermal resistance, and evaporative resistance have been used successfully to evaluate the thermal comfort of fabrics (Barker & Scruggs, 1996; Lee & Obendorf, 2007; Zuo & McCullough, 2005). Attempts have also been made to evaluate physical sensorial comfort based on fabric mechanical properties, such as stiffness, flexural rigidity, breaking load and elongation, bursting and tear strengths and surface roughness (Barker & Scruggs, 1996; Cowan et al., 1988; Rego et al., 2010). Small-scale laboratory tests are a practical alternative to expensive, time-consuming wear trials; however, they do not take into account factors related to garment fit and design. Full-scale thermal manikin tests, on the other hand, take into consideration not only fabric properties but garment features and fit on a human form. Several newly-developed manikins simulate human sweating and provide information about heat exchange by evaporation (Fan & Qian, 2004; McCullough, 2005; Tamura, 2006). Some manikins also incorporate the effects of human movement with walking or cycling simulation (Holmer, Gavhed, et al., 1992; Kuklane, 2008). Manikin testing may be more complex, difficult to control, time-consuming or expensive than fabric testing; however, results from manikin testing are expected to be more relevant and realistic. Laboratory measures of textiles and garments are convenient for comparing different fabrics and garments; however, they exclude the complex combination of environmental conditions, human responses and the interactions among the environment-clothing-human system.

Despite the number of studies in the area, most have focused on effects of one or more fabric properties on physiological and physical comfort, such as permeability (Epstein et al., 2013; Shalev et al., 1996), thermal resistance (Barker & Scruggs, 1996; Frydrych et al., 2009), water vapour resistance (Frydrych et al., 2009; Guo et al., 2008; Lee & Obendorf, 2007), mechanical properties (Barker &

Scruggs, 1996; Cowan et al., 1988) and garment design (Adams & Keyserling, 1995; McLellan, Boscarino, & Duncan, 2013). Very few studies have focused on the prediction of physiological strain and physical burden based on fabric and garment properties (Holmer, 1988). Understanding the relationships between fabric/garment properties and the associated thermo-physiological strain and physical burden of CPC on the wearer is still limited. There is a gap between the studies focused on the analysis and measurement of textile and garment properties and those evaluating human responses. A systematic approach is needed to serve as a bridge between research from two perspectives and to offer a reasonable prediction of thermo-physiological strain and physical burden of CPC based on the material properties and garment parameters.

The current chapter summarizes the third research project of this dissertation following the characterization of comfort related fabric properties and the analyses of clothing ergonomics. The purpose of this research is to determine the effects of three different CPC on thermo-physiological strain and physical burden during moderate treadmill exercise in temperate environmental conditions.

Methods

Participants

Fifteen active, healthy males completed all parts of the experiment. The mean (±SD) physical characteristics of the participants were as follows: age 26.6 ± 4.5 y; mass 73.9 ± 7.5 kg; height 180.2 ± 6.8 cm; and, peak oxygen uptake ($\dot{V}O_{2peak}$) 52.2 ± 3.7 ml·kg^{-1}·min^{-1}. Subjects provided written informed consent to participate in the project that had previously been approved by the University of Alberta Health Research Ethics Board (Biomedical Panel). Medical screening of each individual was completed by a physician to assure the safe use of the ingestible core temperature capsule.

Garments

A control garment system and three types of chemical protective coveralls worn over the control system were used in this study (Figure 5.1). The control garment system included a long-sleeved 100% cotton, knit shirt and 88/12% cotton/nylon twill weave pants. Shirts, pants and coveralls were available in different sizes for the participants to choose their best fit. The descriptions of the design and structure of the CP coveralls, Tyvek®, Tychem® and Gulf are given in Chapter 3, Table 3.1 and Appendix 1.

Prior to testing and between trials, garments were stored under environmental conditions of 20 ± 3°C and <25% relative humidity for at least 48 hours. After a test, each CPC garment was air dried using an electrical fan for at least 4 hours. Control garments were washed and tumble dried between trials.

Preliminary procedures

Participants were screened by a physician for any gastrointestinal (GI) disorders that would contraindicate the use of the ingestible core temperature capsules. The physician also screened participants for pre-existing conditions that would contraindicate exposure to heat stress, specifically a personal or family history of malignant hyperthermia or risk of being a carrier of sickle cell anemia. Participants were further screened on medical contraindications to exercise with the Physical Activity Readiness Questionnaire (PAR-Q Plus).

A graded exercise test was completed during the first laboratory session with the participants dressed in the Control garment ensemble. Peak oxygen consumption ($\dot{V}O_{2peak}$) and peak heat rate (HR_{peak}) were measured to characterize fitness level and to provide information to monitor thermo-physiological stress during the prolonged exercise protocol. The graded exercise test consisted of a constant speed (93.9 $m \cdot min^{-1}$) walking protocol on a motorized treadmill (Standard Industries, Fargo, ND). The test began at a grade of 0% and the grade was increased 2% every minute until volitional exhaustion. The highest 30-s $\dot{V}O_2$ value was accepted as $\dot{V}O_{2peak}$. The highest heart rate observed during the test was recorded as HR_{peak}.

Experimental procedures

In four sessions on separate days, subjects walked on the treadmill at 93.9 $m \cdot min^{-1}$, 4% grade for 60 minutes at ambient conditions of 23 ± 2°C and 0-30% relative humidity. An electrical fan was used for controlled air movement on the treadmill. The air speed on the treadmill was 1.2 $m \cdot s^{-1}$. The treadmill was set to represent a moderate workload consistent with other projects of work intensity in CPC (Dorman & Havenith, 2009; Heled et al., 2004; Levine et al., 2001; Tikuisis, McLellan, & Selkirk, 2002; Vernieuw, Stephenson, & Kolka, 2007). To avoid possible effects of fatigue from previous tests, any two sessions were separated by at least 48 hours. For three sessions a different CPC was worn over the Control garments and in one session only the Control garments were worn. The four sessions were randomly assigned to take place at approximately the same time of the day (±2 hours).

A schematic of the experimental session is given in Figure 5.2. Between five and six hours before each experimental trial, an ingestible core temperature capsule (VitalSense, Philips Respironics, Bend, OR) was swallowed by the participant to monitor core temperature (T_c). The subject brought his own athletic shoes (the same shoes were worn for all the sessions). Attempts were made to standardize pre-trial behaviours, with participants asked to avoid strenuous exercise, alcohol and caffeine within 24 hours. When a participant arrived, he was asked a few questions regarding sleep, food and physical activities prior to the test. This pre-trial survey gathered information related to the reliability of the human subject. They were also asked to be normally hydrated, and this was verified by specific gravity of urine of $\leq$ 1.020 on arrival at the lab. Following the survey of pre-trial behaviour, the pre-test nude weight of the participant was recorded. The investigator then attached the heart rate monitor and VitalSense dermal temperature patches to the participant. The participant was dressed in the designated CPC with the Control garment underneath. After the pre-test clothed weight was measured, the participant started walking slowly on the treadmill. The warm-up period included three minutes walking at 93.9 $m \cdot min^{-1}$, 2%. The elevation of the treadmill was then brought to the designated level, 93.9 $m \cdot min^{-1}$, 4% for the duration of the test. In all the tests conducted with the fifteen participants, no subject had to discontinue their tests prematurely. Following three minutes cool-down at 67.1 $m \cdot min^{-1}$, 0%, the post-test clothed weight was determined and documented. The post-test nude weight was measured after the participant had undressed and towel dried his skin.

Measurements and calculations

Expired gases were collected using a two-way breathing valve (Hans Rudolph, Kansas City, MO, USA). Expired gases and ventilatory parameters were measured and calculated using a metabolic measurement system (TrueOne, ParvoMedics, Salt Lake City, UT, USA). Calibration of the system was performed according to the manufacturer's specifications immediately prior to each test. Calibration was checked immediately following each test and there were no instances where calibration failed to be maintained during a test. In order to minimize any drift in calibration due to excess moisture accumulation, the sample hose and mixing chamber were replaced at 30 minutes. For all 60 tests, this was completed in less than 4.5 min between the 30-min and 35-min time points. No data were lost.

Core temperature was recorded every 5 minutes throughout the tests. Mean skin temperatures were obtained from 4 wireless VitalSense dermal patches affixed to the standardized sites on the right chest, arm, thigh, and calf (Ramanathan, 1964). Temperatures were delivered via wireless signals to the same external monitor used for the core temperature measurements. The weighted mean skin temperature (T_{sk}) was calculated to the nearnest 0.1 °C using the equation:

$$T_{sk} = 0.3T_{chest} + 0.3T_{bicep} + 0.2T_{thigh} + 0.2T_{calf} \quad \text{eq. 5.1}$$

(Ramanathan, 1964).

Heart rate (HR) was continuously monitored using telemetry (Polar Beat, Electro, Lachine, QC).

Physiological Strain Index (PSI) was calculated using a modification to Moran's equation (Moran, Shitzer, & Pandolf, 1998):

$$PSI = 5(T_c - T_{c0})/(40.0 - T_{c0}) + 5(HR - HR_0)/(HR_{peak} - HR_0) \quad \text{eq. 5.2}$$

Where, T_{c0} = core temperature at the beginning of each test;

HR_0 = resting heart rate of each participant;

HR_{peak} = peak heart rate of each participant determined during graded exercise test.

Change in body mass was calculated for each participant in each garment system by comparing the pre-test and post-test nude mass of the subject. There was no fluid intake or elimination during the test protocol.

Subjective measurements including, rating of perceived exertion (RPE), hotness in clothing, wetness in clothing, restriction to arms and restrictions to legs were recorded every five minutes throughout the tests. Rating of perceived exertion was determined using a 15-point scale (range 6-20, Appendix 8) (Borg, 1982). Hotness/wetness in clothing were determined using a five-point subjective rating scale (International Organization for Standardization, 1995), where 0 = no change, 1 = slightly hot/wet, 2 = hot/wet, 3 = very hot/wet and 4 = extremely hot/wet. Restriction to arms/legs (RTA/RTL) were determined using a similar scale, where 0 = no restriction, 1 = slightly restricted, 2 = restricted, 3 = very restricted, and 4 = extremely restricted. The increments of the subjective rating scales were assumed to be equal and were presented and explained to the participants in this way. For example, a rating of "2" (restricted) for restriction to arms would be twice as restrictive as "1" (slightly restricted) and a rating of "4" (extremely restricted) would be twice as restricted as "2".

Statistical analysis

Statistical comparisons were made among the three CPC systems and the Control garment system. Analysis of variance (ANOVA) with repeated measures was used to analyze $\dot{V}O_2$, T_c, T_{sk}, HR, PSI, $\dot{V}_E$, $\dot{V}_E/\dot{V}O_2$, RPE, hotness in clothing, wetness in clothing, restriction to arms and restriction to legs for each 10-min test time interval (for HR, T_c, T_{sk}, PSI, RPE, hotness/wetness in clothing and restriction to arms/legs, the initial results at t=0 min were included and analyzed). ANOVA was also used to compare the mean change in body mass in different garment systems. For all tests a significance level of p <0.05 was used. Where significant effects or interactions were found, post-hoc comparisons using the Tukey HSD test were made to locate significant differences. All data are presented in the figures with error bars as the mean (± standard error). Pearson's correlation analysis was used to determine the relationships between change of body mass and body temperature responses and between some perceptual and physiological responses.

Results

Oxygen consumption ($\dot{V}O_2$)

The change of relative oxygen consumption (oxygen consumption per kg nude mass of the subject), $\dot{V}O_{2\text{-}N}$ was plotted in Figure 5.3. $\dot{V}O_{2\text{-}N}$ in the Control garment, Tyvek® and Gulf did not change significantly throughout the tests, while $\dot{V}O_{2\text{-}N}$ in Tychem® increased significantly (p=0.019) from 22.3 ml·kg^{-1}·min^{-1} to

24.9 ml·kg^{-1}·min^{-1}. In Figure 5.3, $\dot{V}O_{2\text{-}N}$ in Tychem® showed a significant difference over $\dot{V}O_{2\text{-}N}$ in the Control and Tyvek® at 10 min and beyond. At 20 min and beyond, $\dot{V}O_{2\text{-}N}$ in Gulf was significantly different than the Control. No significant differences in $\dot{V}O_{2\text{-}N}$ were found between the Control and Tyvek® or between Gulf and Tychem® at any point of testing.

The change of $\dot{V}O_2$ per kg total mass (mass of clothed subject), $\dot{V}O_{2\text{-}T}$ during exercise was calculated and shown in Figure 5.4. There were no differences in $\dot{V}O_{2\text{-}T}$ for the Control, Tyvek® and Gulf throughout the test. At 10 min and starting at 40 min, $\dot{V}O_{2\text{-}T}$ of Tychem® was higher than the Control. Significant differences in $\dot{V}O_{2\text{-}T}$ were found between Tychem® and Tyvek® at 10 min, 30 min, 50 min and 60 min. At 60 min, $\dot{V}O_{2\text{-}T}$ for Tychem® was also higher than the multi-layer CPC Gulf.

Core temperature (T_c)

The changes in T_c during the four trials in the Control garment and the three different CPC is presented in Figure 5.5. The core temperature increased by 0.5°C in the Control, 0.7°C in Tyvek®, 1.0°C in Gulf and 1.8°C in Tychem® when the start and end values of the whole test period were compared. At 30 min, the T_c in Tychem® was significantly higher than in the Control. At 40 min, the T_c in Tychem® became significantly higher than Tyvek® and Gulf. At 50 min, the T_c in Gulf also became significantly higher than in the Control. These differences remained throughout the period of testing.

Weighted mean skin temperature (T_{sk})

As shown in Figure 5.6, at 0 min, T_{sk} in all CP coveralls was significantly higher than in the Control. T_{sk} in Tychem® and in Tyvek® was also significantly different from each other. At 10 min and 20 min, T_{sk} showed significant differences according to the clothing type with the exception of Gulf vs. Tychem®. At 30 min, T_{sk} was found in the order of highest to lowest in Tychem®, Gulf, Tyvek® and Control. All the differences were significant and lasted throughout the entire test.

Change in body mass

Three body and clothing weight parameters calculated from the pre- and post- nude and clothed mass was reported in Table 5.1. The change in nude body mass (ΔNBM) was calculated by subtracting post-test nude weight from pre-test nude weight. The change in clothed body mass (ΔCBM) was the difference of pre-test clothed weight and post-test clothed weight. The weight of clothing ensemble (WC) was the difference of pre-test clothed mass and pre-test nude mass. The mean ΔNBM of Tychem® and Gulf were 1.43 kg and 1.26 kg respectively. These numbers were higher ($p<0.05$) than that of the Control at 0.75 kg. For Tyvek®, the mean ΔNBM was 1.06 kg, which was significantly lower than Tychem® but not different from Gulf and the Control. Although Tychem® had the highest ΔNBM, its ΔCBM (0.26 kg) was significantly lower than values from all the other conditions. Significant difference on ΔCBM was also found between the Control (0.57 kg) and Tyvek® (0.51 kg). The results on WC show that the heaviest and second heaviest clothing ensembles were Gulf and Tychem®. The Control and Tyvek® were lighter ensembles without significant differences between them.

Heart rate (HR)

As shown in Figure 5.7, during the test, there was a slight increase (from 103 $b \cdot min^{-1}$ to 116 $b \cdot min^{-1}$) in heart rate in the control condition, which demonstrated the impact of the moderate exercise load on the cardiovascular responses. Heart rate in Tychem® started to show significant difference over the Control as early as 10 minutes of exercise. At 20 min, heart rate in Tychem® was higher than both the Control and Tyvek®. At 30 min, heart rate in Gulf became significantly higher ($p<0.05$) than in the Control. Starting at 40 min, heart rate in Tychem® was also found to be significantly higher than Gulf. Heart rate in the Control vs. Tyvek® and Tyvek® vs. Gulf did not show significant differences throughout the entire exercise period.

Physiological Strain Index (PSI)

The changes in PSI are presented in Figure 5.8 for different clothing types. At 0 min, PSI in Tychem® was significantly higher than in the Control. At 10 min, PSI in Tychem® became significantly higher than in Tyvek®. Then at 20 min, the difference in PSI between the Control and Gulf became significant with Gulf higher than the Control. From 30 min to 60 min, more significant differences were found in PSI. In Tychem®, the PSI was significantly higher than in any other clothing system. In Gulf, the PSI was also significantly higher than in the Control during the last 30 minutes.

Minute ventilation ($\dot{V}E$)

The results on $\dot{V}_E$ (Figure 5.9) are similar to $\dot{V}O_2$, with no significant change throughout the tests in the Control, Tyvek® and Gulf. Ventilation in Tychem® increased significantly ($p<0.001$) from 42.2 $L \cdot min^{-1}$ (at 10 min) to 53.9 $L \cdot min^{-1}$ (at 60 min). In Tychem®, $\dot{V}_E$ showed significant difference than $\dot{V}_E$ in the Control and Tyvek® at most times throughout the whole testing period. In the last 20 minutes, $\dot{V}_E$ in Tychem® was also significantly higher than in Gulf.

$\dot{V}_E/\dot{V}O_2$ (the ventilatory equivalent for oxygen)

The $\dot{V}_E/\dot{V}O_2$ ratio is displayed in Figure 5.10. At 50 min, the $\dot{V}_E/\dot{V}O_2$ value for Tychem® was significantly higher than the Control. At the end of testing period, $\dot{V}_E/\dot{V}O_2$ value for Tychem® was higher than Control, Tyvek® and Gulf.

Rating of perceived exertion (RPE)

At 0 min, RPE (Figure 5.11) in Tychem® was significantly higher than in the Control. At 10 min, RPE in Gulf also became significantly higher than in the Control. Then at 20 min, the difference in RPE between Tychem® and Tyvek® became significant with Tychem® higher than Tyvek®. At 50 min, RPE in Tychem® was higher than in Gulf.

Hotness in clothing (HIC)

The mean perceived HIC reported by the participants was different ($p< 0.05$) for different clothing at the beginning of the test. As shown in Figure 5.12, at 0 min, HIC in the Gulf garment was significantly higher than in the Control or in the Tyvek® garments. In Tychem®, the HIC was also significantly higher than in the Control. This indicates that after the dressing and warm up periods, heat accumulated in these garments already differed. During the first half of the exercise, greater differences among the clothing systems were reported. At 30 min, HIC was significantly different for all the clothing types except Tyvek® and Gulf. The significant differences continued to be reported throughout the test.

Wetness in clothing (WIC)

The mean perceived WIC was assessed by the participants to be significantly higher in Tychem® than in either the Control or Tyvek® garments at the beginning of the exercise. During the exercise, WIC was significantly greater in all of the CP coveralls than in the Control, as shown in Figure 5.13. At the end point, WIC in Tychem® was significantly greater than in Tyvek® as well. Tyvek® vs. Gulf and Gulf vs. Tychem® showed no difference throughout the entire period.

Restriction to arms and legs (RTA and RTL)

The level of restrictions caused by the garments was found to differ (Figure 5.14 and 5.15). Tychem®, the stiffest material, impaired both arm and leg movements the most. Gulf also restricted movement significantly due to its heaviness and thickness. Tyvek®, the lightest coverall, did not show significant restriction to arm and leg movements over the Control garment.

Discussion

The primary finding of the experiment was that all three CP coveralls induced thermo-physiological strain and/or physical burden at different levels. The Tyvek® garment was found to be the most comfortable CP clothing system with the least physiological strain and physical burden. Tychem® was the most uncomfortable with Gulf being somewhere in the middle. This is not surprising since Tychem® provides a greater level of protection than either the Gulf or Tyvek® and this protection is achieved through encapsulation in an impermeable material. The protection of Gulf is achieved through its thickness (the absorbent layer). As mentioned in the introduction, impermeability and thickness are known to cause discomfort and physiological strain.

There was a clear effect of wearing the selected CP garments on oxygen consumption. It was found that wearing Tychem® and Gulf coveralls increased the oxygen consumption by 10.2% (2.2 $ml \cdot kg^{-1} \cdot min^{-1}$) and 7.7% (1.6 $ml \cdot kg^{-1} \cdot min^{-1}$) during the entire controlled moderate exercise. These increases were similar to the findings of Dorman and Havenith (2009) and Rissanen et al. (2008), who observed 8-14% higher energy cost in chemical protective ensembles over the control garments.

In these studies (Dorman & Havenith, 2009; Rissanen et al., 2008), the additional weight of the CPC, extra fabric layers, friction and the stiffness of the CPC were considered to be contributing factors to the increase in oxygen consumption. However, these researchers did not quantify the contributions of additional weight and other textile/garment properties to the increase in oxygen consumption. This current study provides results to confirm that additional clothing weight was not the only factor leading to the increase in oxygen consumption. As listed in Table 5.1, the heaviest system was Gulf, 3.86 kg, which was significantly higher than all of the other clothing systems. The overall mean $\dot{V}O_{2\text{-}N}$ (Figure 5.3) for participants in Gulf during the 60 minutes exercise was found to be higher ($p<0.05$) than for the two lightest clothing systems, the Control and Tyvek® by 1.6 and 1.8 $ml\cdot kg^{-1}\cdot min^{-1}$, respectively. However, overall mean relative $\dot{V}O_{2\text{-}N}$ for participants in Tychem® was found to be significantly higher than in Gulf by 0.5 $ml\cdot kg^{-1}\cdot min^{-1}$ despite the fact that Tychem® was lighter than Gulf.

It is known that garment bulkiness, stiffness, inability to stretch and friction between fabric layers will contribute to the physical burden on the wearer and restrict their movements (Fourt & Hollies, 1970; Watkins, 1995). When work must be accomplished by straining clothing through compression, bending, stretching, and shearing actions or by sliding one fabric against another, energy that could be used to accomplish a task is wasted (Wen, Song, & Duncan, 2012). The results of fabric testing reported in Chapter 3, showed Tychem® to be the most rigid material among the group according to its mechanical properties. The rigidity of the Tychem® fabric and the subsequent bulkiness were expected to interfere with the walking movement on the treadmill thus resulting in further increased oxygen consumption. To verify this hypothesis, the mean $\dot{V}O_{2\text{-}T}$ during exercise was calculated and the results are shown in Figure 5.3.

In comparison with Figure 5.2, the variations in Figure 5.3 accounted for effects on oxygen consumption of measured textile/garment properties except clothing weight. It was clear that when the effect of garment weight was included (Figure 5.2), $\dot{V}O_{2\text{-}N}$ in the heaviest CPC Gulf was significantly higher than in the Control or Tyvek® at the end of the test. Throughout the test, it was not different from Tychem®. However, in Figure 5.3, when the effect of clothing weight was excluded, $\dot{V}O_{2\text{-}T}$ at 60 min for Gulf was found to be significantly lower than Tychem® and not different from the Control and Tyvek®. This comparison provides adequate evidence for the fact that garment weight alone does not indicate the changes in oxygen consumption. Detailed correlation and regression analyses between oxygen consumption and textile mechanical properties are presented in Chapter 6.

The results for core and skin temperatures suggest that there was uncompensable heat stress in Tychem®. The T_c in Tychem® (see Figure 5.4) climbed continuously in a linear relationship ($r=0.866$, $p<0.01$) over time with a total increase at 1.8°C. This trend indicated that heat dissipation from the clothing system was not sufficient therefore heat was stored resulting in an increase in core temperature. Similar results were reported by Marzalk, Bartkowiak, and Lezak (2009), for an impermeable CP coverall. They found the coverall increased the external auditory canal temperature by 1.1°C during 30 minutes of treadmill walking at 3 $km \cdot h^{-1}$ in 40°C, 30% RH and wind speed of 0.2 $m \cdot s^{-1}$ (Marzalek, Bartkowiak, & Lezak, 2009). In a 30 minute 400 Kcal/hr walking-curling-walking procedure, rectal temperature in an industrial vapour-barrier protective clothing was found to increase by 0.90°C in a temperate environment (Reneau, Bishop, & Ashley, 1997). The average energy expenditure of the current study was calculated as 475 Kcal/hr based on average oxygen consumption and body mass at 22.3 $ml \cdot kg^{-1} \cdot min^{-1}$ and 73.9 kg. The increase in T_c in Gulf after 60 min walking was 1.0°C, which was significantly higher than the Control session (0.5°C). Reneau et al. (1997) observed 0.5°C elevation in rectal temperature in a similar military chemical suit after 30 minutes work at 400 Kcal/hr. The change in T_c for Tyvek® was 0.7°C, which was significantly higher than the Control and significantly lower than for Tychem®. This response was consistent with those found by other researchers (Holmer, Nilsson, Rissanen, Hirata, & Smolander, 1992; Turpin-Legendre & Meyer, 2007).

The results for skin temperature also suggested significantly higher thermal strain in Tychem® (see Figure 5.5). Overall mean (±SEM) T_{sk} was 33.9 ± 0.05°C, 34.9 ± 0.05°C, 35.6 ± 0.06°C and 36.3 ± 0.07°C in the Control, Tyvek®, Gulf and Tychem®, respectively ($p < 0.05$). For the Control, Tyvek® and Gulf, after 20 min, body surface cooling effectively prevented T_{sk} from escalating; whereas in Tychem®, T_{sk} continued to rise throughout the exercise. Mean skin temperature in impermeable chemical suits was found to increase by as high as 4 to 5°C (Marzalek et al., 2009), whereas permeable military chemical suits and Tyvek® elevated T_{sk} by 0.2 to 2.2 °C during different protocols and in various environments (Holmer et al., 1992; Reneau et al., 1997).

The results for ΔNBM showed the loss in body mass was greatest in the impermeable Tychem® (1.43 kg). However, the mass loss was predominately from liquid sweating and was confirmed by the value of ΔCBM, which was only 0.26 kg for Tychem®. The ΔCBM value reflected how much mass had been lost by evaporation through sweating and respiration during the test. The amount of the accumulated sweat in clothing can be calculated by finding the difference between ΔNBM and ΔCBM. The results (Figure 5.15) indicated that during the experiment with Tychem® the amount of sweat which evaporated (ΔCBM) was significantly lower ($p<0.05$) and the amount of sweat which accumulated in the clothing (ΔNBM - ΔCBM) was significantly higher ($p<0.05$) than in experiments with the Control, Tyvek® and Gulf. The sweat distribution with Tychem® was 81% as accumulated sweat and 19% as evaporated sweat. In Marzalek et al. (2009), sweat distribution with an impermeable chemical suit was determined as 65% accumulated sweat and 35% evaporated sweat. The Pearson correlations (Table 5.2) between ΔCBM and change in core temperature (ΔT_c), ($r = -0.733$, $p<0.01$), indicated that an increase in evaporated sweat results in a smaller increase in core temperature. There was also a weak negative linear relationship between ΔCBM and change in weighed mean skin temperature (ΔT_{sk}) ($r=-0.491$, $p<0.01$). An increase in ΔNBM, on the other hand, did not relate to a lower core or skin temperature as listed in Table 5.2.

The increase in HR during the 60 minutes treadmill walking (93.9 $m\cdot min^{-1}$, 4%) while dressed in Tychem®, Gulf and Tyvek® were 54 ± 11.5 $beats\cdot min^{-1}$, 35 ± 14.2 $beats\cdot min^{-1}$ and 26 ± 10.2 $beats\cdot min^{-1}$, respectively. These results were consistent with those reported by other researchers. Marzalek et al. (2009) observed HR increases of 50-60 $beats\cdot min^{-1}$ with impermeable coveralls while subjects walking on treadmill at 3 $km\cdot h^{-1}$ for 50 minutes under 40°C, 30% RH conditions. Levine et al. (2001) observed HR increases of 40-55 $beats\cdot min^{-1}$ when subjects carried out 50 minutes treadmill exercise in military chemical protective ensembles under 35°C, 50% RH. Turpin-Legendre and Meyer (2003) observed mean HR of 119 ± 23 $beats\cdot min^{-1}$ with Tyvek® when subjects performed normal abatement tasks including brushing asbestos off the walls and ceiling. In the current study, the overall mean HR in Tyvek® during 60 minute treadmill walking was 121±17.0 $beats\cdot min^{-1}$. Overall, HR responses showed a similar trend as the temperature results, but with an earlier appearance of significant differences. Increase in HR implies thermal strain, and at the same time it is a physiological response to compensate for fluid loss. Therefore, the significant difference in HR was accelerated and enlarged due to the double effects from the heat stress and the reduction of plasma. The calculated index, PSI also demonstrated differences of a greater magnitude and significance than T_c.

Significant physiological strain in Tychem® was also demonstrated in the ventilatory responses. $\dot{V}_E$ in Tychem® during the last 20 min was significantly higher than for all other conditions. It was revealed that during a maximal treadmill walking protocol in thermal protective clothing, most of the increase in $\dot{V}_E$ was due to the increase in $\dot{V}O_2$ (Dreger et al., 2006). The variations in $\dot{V}_E$ have been further analyzed by plotting the ventilatory equivalent for oxygen ($\dot{V}_E/\dot{V}O_2$) across time. By doing this, the increment in $\dot{V}_E$ due to the increase in $\dot{V}O_2$ has been removed. In Figure 5.9, the discrepancy in $\dot{V}_E/\dot{V}O_2$ between Tychem® and the other conditions represents the impact of thermal strain on ventilation (Nelson, Haykowsky, Mayne, Jones, & Petersen, 2009; White, 2006).

Subjective rating of perceived exertion agreed with the objective physiological $\dot{V}O_2$ and HR responses (Pearson correlation: $r = 0.527$ and $r = 0.692$, $p < 0.01$) (Table 5.3). Tychem® and Gulf were found with higher RPE for different reasons. According to the subjects' comments, the heaviness of Gulf and the stiffness of Tychem® were the main reasons responsible for the higher RPE. However, heat stress could also play a very important role in the RPE through combined effects of reduced brain activity, impaired neuromuscular function and decreased cerebral blood flow (Cheung & Sleivert, 2004). White et al. (1991) found that the use of CPC increased the perceived ratings of work by approximately 1 rating point on a 7-point scale during treadmill walking at 4 km/hr. Further research on perceived exertion was carried out by creating a subjective heat strain index using perceived exertion and perceptions of thermal sensation (Tikuisis et al., 2002).

The results of the subjective evaluation of hotness in clothing (HIC) demonstrated more differences than the objective temperature measurements (Figure 5.11). The four garments were clearly ranked by the subjects, with Tychem® being the hottest, the Control being the least hot and Tyvek® and Gulf (with no differences between each other) ranked in the middle. There were significant correlations between HIC and T_c, HIC and T_{sk} and HIC and PSI (Table 5.3). Gulf and Tyvek® were also found with no difference on wetness in clothing. Wetness in clothing (WIC) in Tychem®, Gulf and Tyvek® were found higher than the Control. A moderate significant correlation was found between ΔWIC (change in wetness in clothing) and ΔNBM-ΔCBM (accumulated sweat), $r = 0.617$, $p < 0.01$, n=53. The positive weak correlation between ΔWIC and ΔNBM (change in nude body mass) was also significant, $r = 0.473$, $p < 0.01$, n = 59. Others (Marzalek et al., 2009; Turpin-Legendre & Meyer, 2003; Vernieuw et al., 2007; White et al., 1991) have shown that subjective perceptions of stress (temperature and sweating in clothing) were increased by CPC use, but few investigations have included the correlation investigation between perceptual and physiological responses (Holmer, Nilsson, et al., 1992). Holmer et al. (1992) observed a strong significant relationship between perceived sweating and skin wetness, $R^2 = 0.88$.

The effect of protective clothing on body movements has been determined using range-of-motion (ROM) (Adams & Keyserling, 1995; Coca et al., 2008; Huck, 1988) and subjective rating of perceived impediment (i.e., garment induced restriction) (Adams & Keyserling, 1996). We are unaware of any literature which relates subjective ratings of perceived restriction to physiological responses. In this current study, the results on RTA and RTL showed very similar trends to RPE. Tychem® and Gulf restricted movements at a higher level than the Control garment and Tyvek®. Subjects' comments on the sources of restrictions included stiffness of Tychem®, heaviness and bulkiness of Gulf, frictions between legs in Tychem® and Gulf, and the restriction caused by the wetted control garment underneath the CPC. Pearson correlation analysis was performed between RTA and $VO_{2\text{-}T}$ and RTL and $VO_{2\text{-}T}$, see Table 5.3. Both pairs showed weak but significant correlations.

Summary

As described in Chapter 3, all garments were a coverall style and similar in construction with a zipper front closure and elastic/Velcro edging on hood and cuffs to hold the garments tight against the face wrists and ankles. To prevent air movement through garment opening, gloves were worn and tape was used at the cuffs and ankles. Of the three CP garments, the Tychem® can provide the greatest protection and its mechanism of protection is impermeability. The Gulf provides a medium level of protection overlapping with the Tychem® as being suitable for protection against vapours, gases and small amount of liquids but not adequate for great amount of liquid. The mechanism of protection for Gulf is by absorption and this garment is penetrable by liquids. The third garment, Tyvek®, is the least protective. The non-woven Tyvek® is liquid repellant, so it is expected to perform better than Gulf against liquid splash hazards, however it is neither impermeable nor absorptive to vapours and gases.

As expected, as the chemical protection of the three garments increased so too did the thermo-physiological strain and physical burden on the wearer. This is shown by the significant higher responses in Tychem® in almost all tested parameters (except RTL not significant than Gulf). Gulf was also found to impair thermo-physiological and physical comfort significantly in comparison to the Control as the significance demonstrated in the results of $\dot{V}O_2$, T_c, T_{sk}, HR, PSI, RPE, HIC, WIC, RTA, and RTL. Tyvek® was identified as the most comfortable CPC among the three coveralls. The results of Tyvek® for T_{sk}, HIC and WIC were the only parameters that were significantly higher than the Control during the exercise, indicating slight thermal discomfort in the Tyvek® garment system.

In summary, the objective and subjective assessment of thermo-physiological and physical comfort was successfully quantified for the selected CP garment systems during the controlled human trials. The subjective responses were significantly correlated to the objective physiological results, indicating that the subjective rating scales used were valid. The effects of specific fabric properties on wearer thermo-physiological strain and physical burden were recognized.

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Table 5.1 Change in body mass and weight of clothing systems

	Change in nude body mass (kg) ΔNBM	Change in clothed body mass (kg) ΔCBM	Weight of clothing ensemble (kg) WC
Control	0.75 ± 0.04[cd]	0.57 ± 0.02[bd]	1.76 ± 0.05[cd]
Tyvek®	1.06 ± 0.09[d]	0.51 ± 0.02[ad]	1.93 ± 0.07[cd]
Gulf	1.26 ± 0.10[a]	0.54 ± 0.01[d]	3.86 ± 0.06[abd]
Tychem®	1.43 ± 0.11[ab]	0.26 ± 0.01[abc]	2.75 ± 0.06[abc]

Values are means ± SEM (n=54, 59 and 59).

Significance ($P < 0.05$) indicated by:

[a] = different from Control; [b] = different from Tyvek®;

[c] = different from Gulf; [d] = different from Tychem®.

Table 5.2 Pearson Correlations between change of body mass and thermal physiological responses

Comparison	r value	p value	n
ΔCBM vs. ΔT_c	-0.733	<0.01	54
ΔCBM vs. ΔT_{sk}	-0.491	<0.01	54
ΔNBM vs. ΔT_c	0.464	<0.01	59
ΔNBM vs. ΔT_{sk}	NS	-	59

Pearson Correlations between change of body mass and thermal physiological responses (before and after exercise) in the following pairs, change of clothed body mass (ΔCBM) and change in core temperature (ΔT_c), ΔCBM and change in weighed mean skin temperature (ΔT_{sk}), change of nude body mass (ΔNBM) and ΔT_c, ΔNBM and ΔT_{sk}.

NS: not significant

Table 5.3 Pearson Correlations between perceptual and physiological responses

Comparison	r value	p value	n
RPE vs. $VO_{2\text{-}N}$	0.527	<0.01	720
RPE vs. HR	0.692	<0.01	780
HIC vs. T_c	0.680	<0.01	780
HIC vs. T_{sk}	0.743	<0.01	780
HIC vs. PSI	0.766	<0.01	780
ΔWIC vs. ΔNBM	0.473	<0.01	59
ΔWIC vs. ΔNBM-ΔCBM	0.617	<0.01	53
RTA vs. $VO_{2\text{-}T}$	0.324	<0.01	720
RTL vs. $VO_{2\text{-}T}$	0.353	<0.01	720

Pearson Correlations between perceptual and physiological responses in the following pairs, rating of perceived exertion (RPE) and oxygen consumption per kg nude mass ($VO_{2\text{-}N}$), RPE and heart rate (HR), hotness in clothing (HIC) and core temperature (T_c), HIC and weighed mean skin temperature (T_{sk}), HIC and PSI, change in wetness in clothing (ΔWIC) and change of nude body mass (ΔNBM), ΔWIC and accumulated sweat ((ΔNBM-ΔCBM), restriction to arms (RTA) and oxygen consumption per kg total mass($VO_{2\text{-}T}$), restriction to legs (RTL) and $VO_{2\text{-}T}$.

Figure 5.1 Test garment systems: control, Tyvek®, Gulf and Tychem® (from left to right)

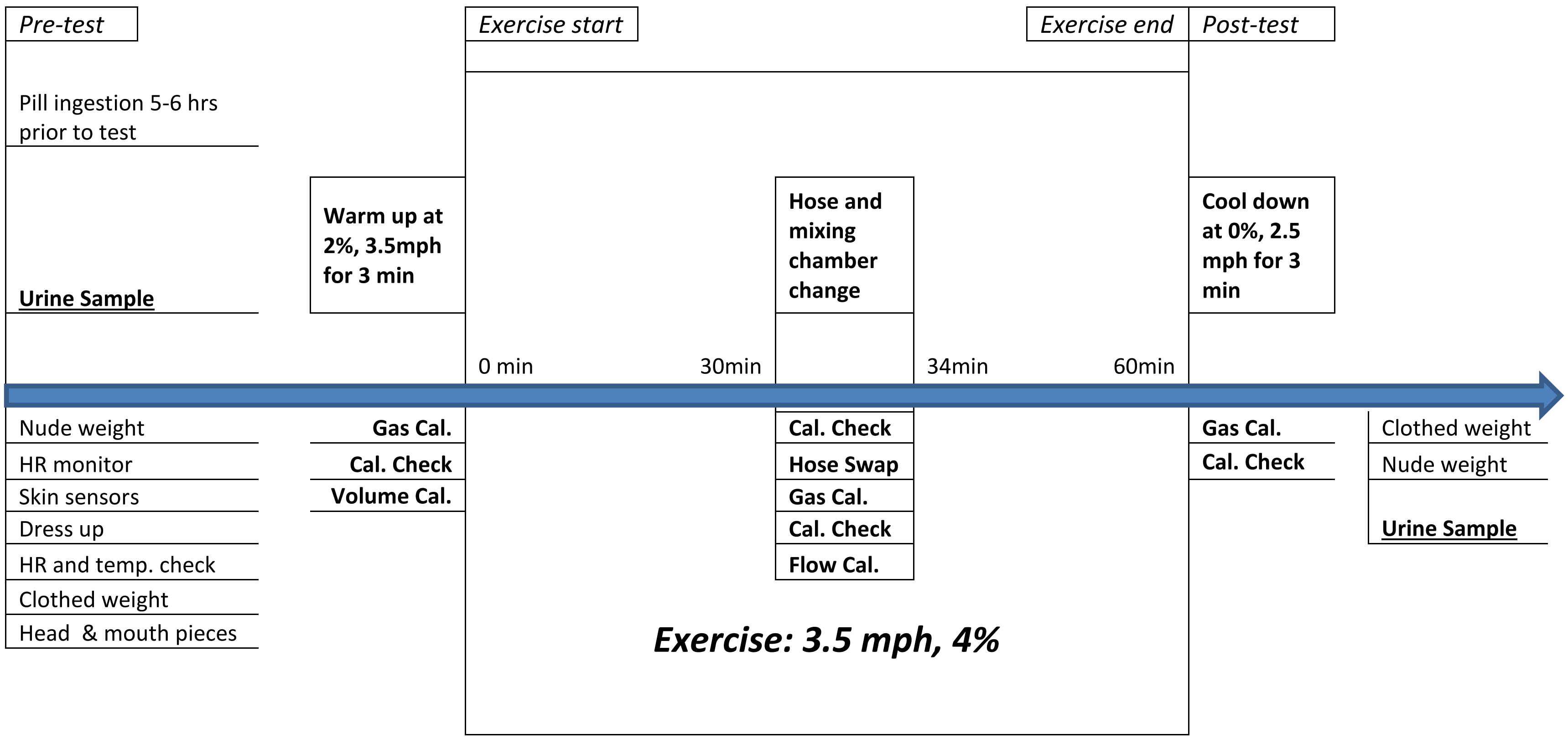
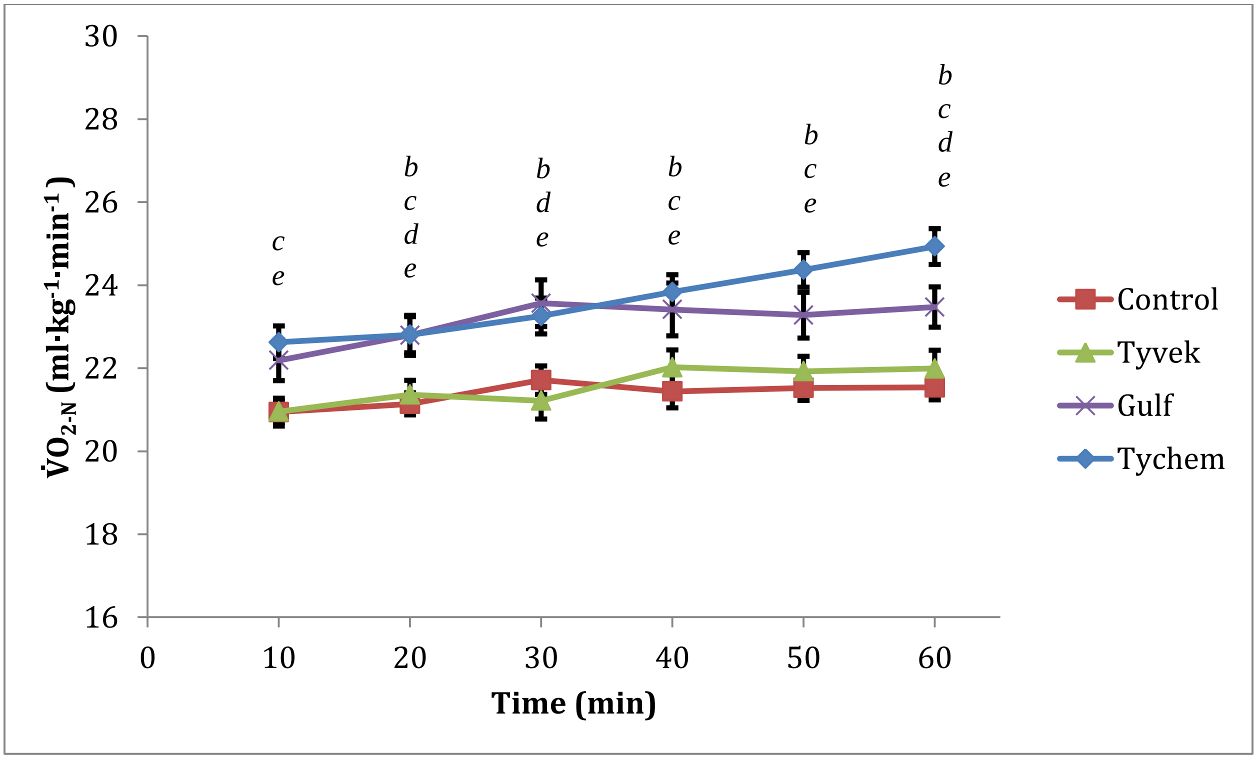
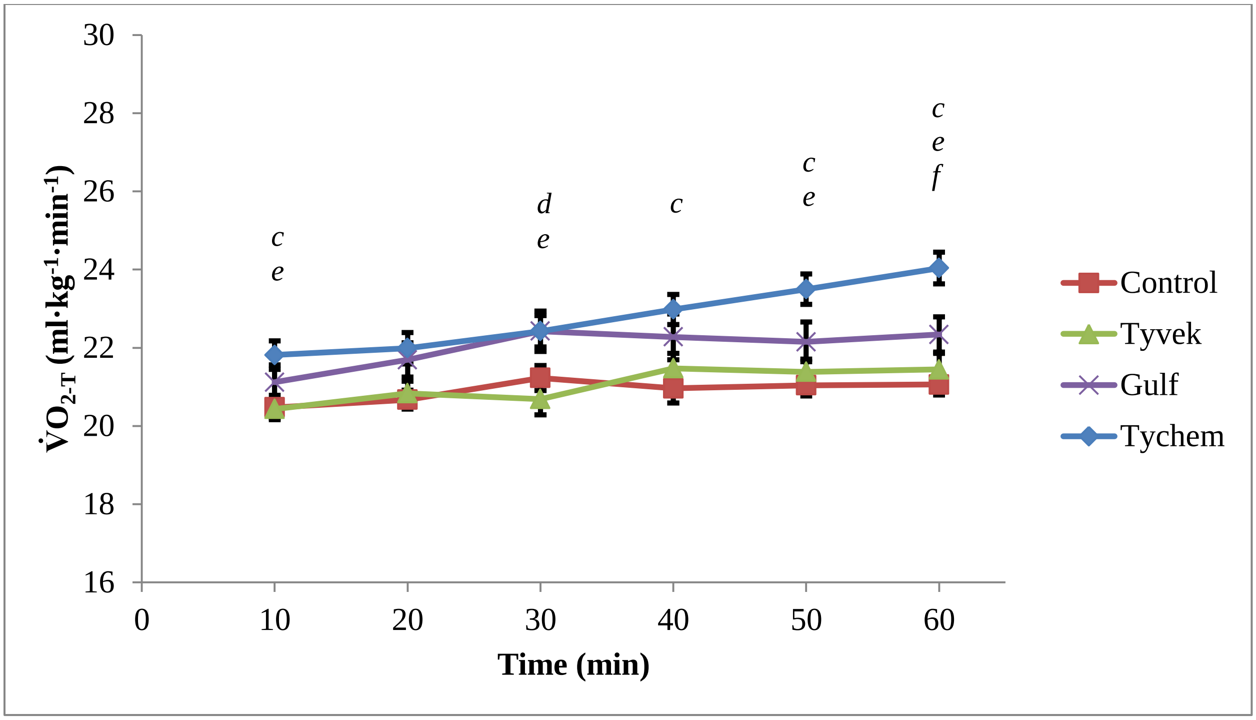


Figure 5.2 Experimental session schematic



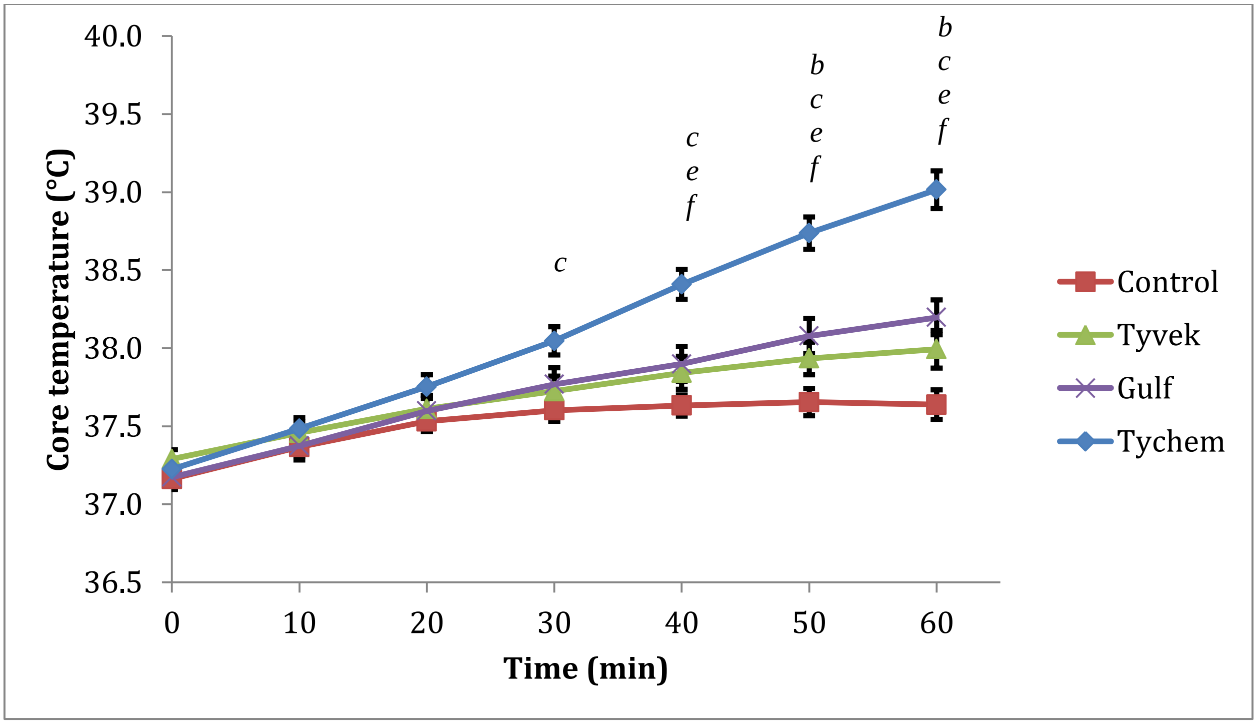
Significance (P <0.05) indicated by *a* (Control vs. Tyvek®), *b* (Control vs. Gulf), *c* (Control vs. Tychem®), *d* (Tyvek® vs. Gulf), *e* (Tyvek® vs. Tychem®) and *f* (Gulf vs. Tychem®)

Figure 5.3 Mean (±SEM) oxygen consumption per kg nude mass ($\dot{V}O_{2\text{-}N}$) during 60 minutes of treadmill exercise for Control and three CP coveralls (n=15)



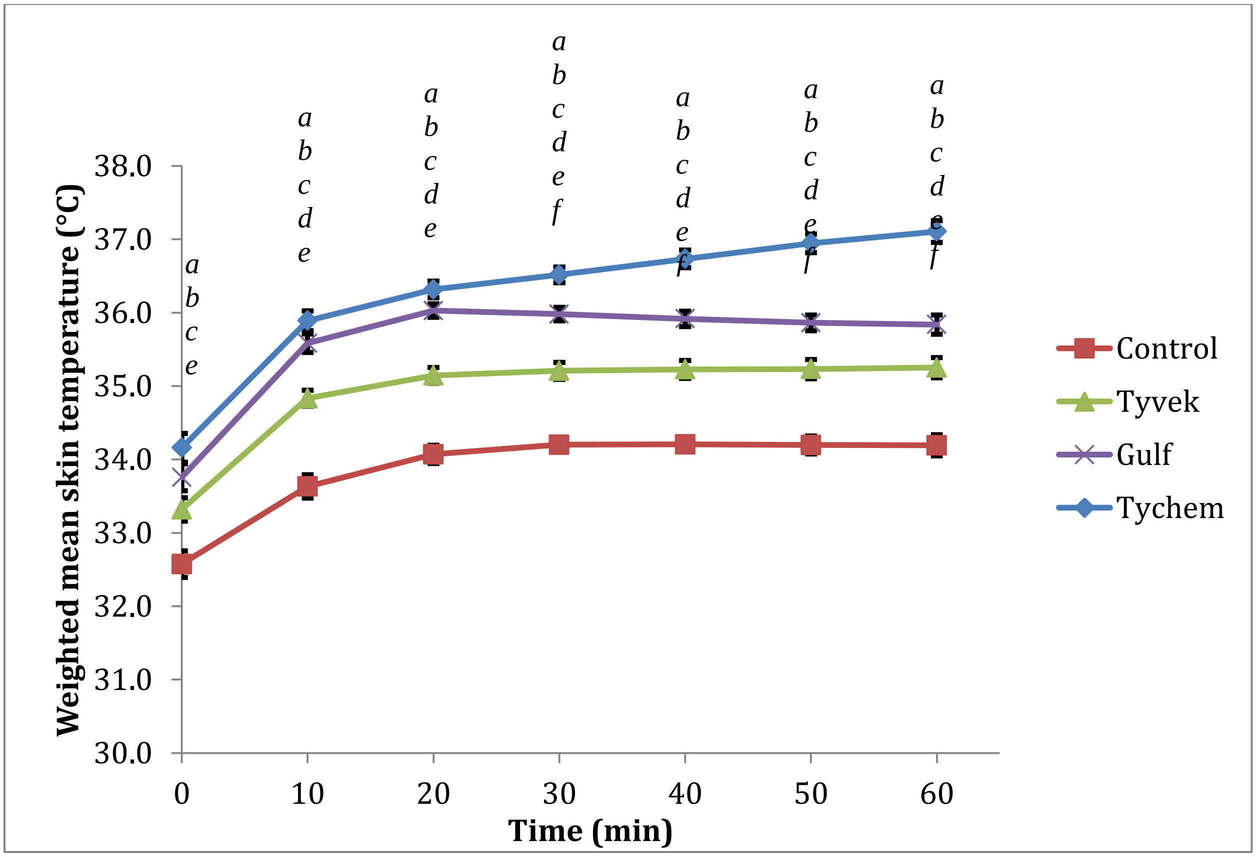
Significance (P <0.05) indicated by *a* (Control vs. Tyvek®), *b* (Control vs. Gulf), *c* (Control vs. Tychem®), *d* (Tyvek® vs. Gulf), *e* (Tyvek® vs. Tychem®) and *f* (Gulf vs. Tychem®)

Figure 5.4 Mean (±SEM) relative oxygen consumption per kg total mass ($\dot{V}O_{2\text{-}T}$) during 60 minutes of treadmill exercise for Control and three CP coveralls (n=15)



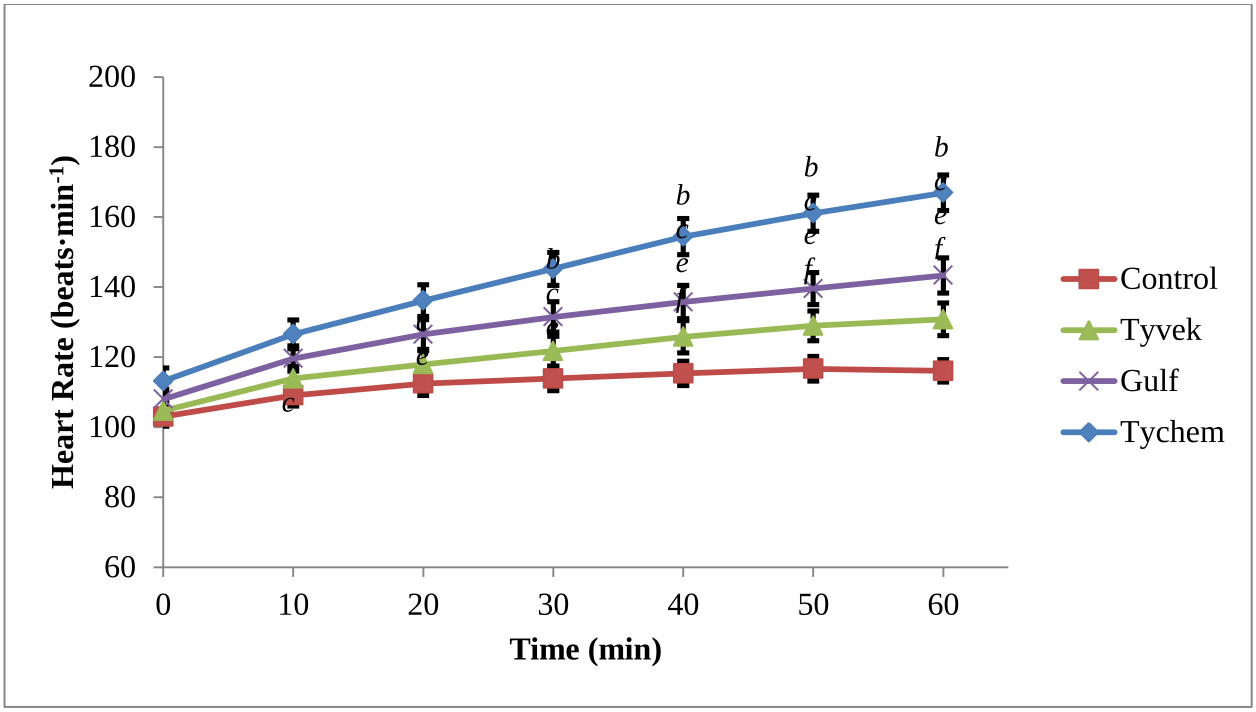
Significance (P <0.05) indicated by *a* (Control vs. Tyvek®), *b* (Control vs. Gulf), *c* (Control vs. Tychem®), *d* (Tyvek® vs. Gulf), *e* (Tyvek® vs. Tychem®) and *f* (Gulf vs. Tychem®)

Figure 5.5 Mean (±SEM) core temperature during 60 minutes of treadmill exercise for Control and three CP coveralls (n=15)



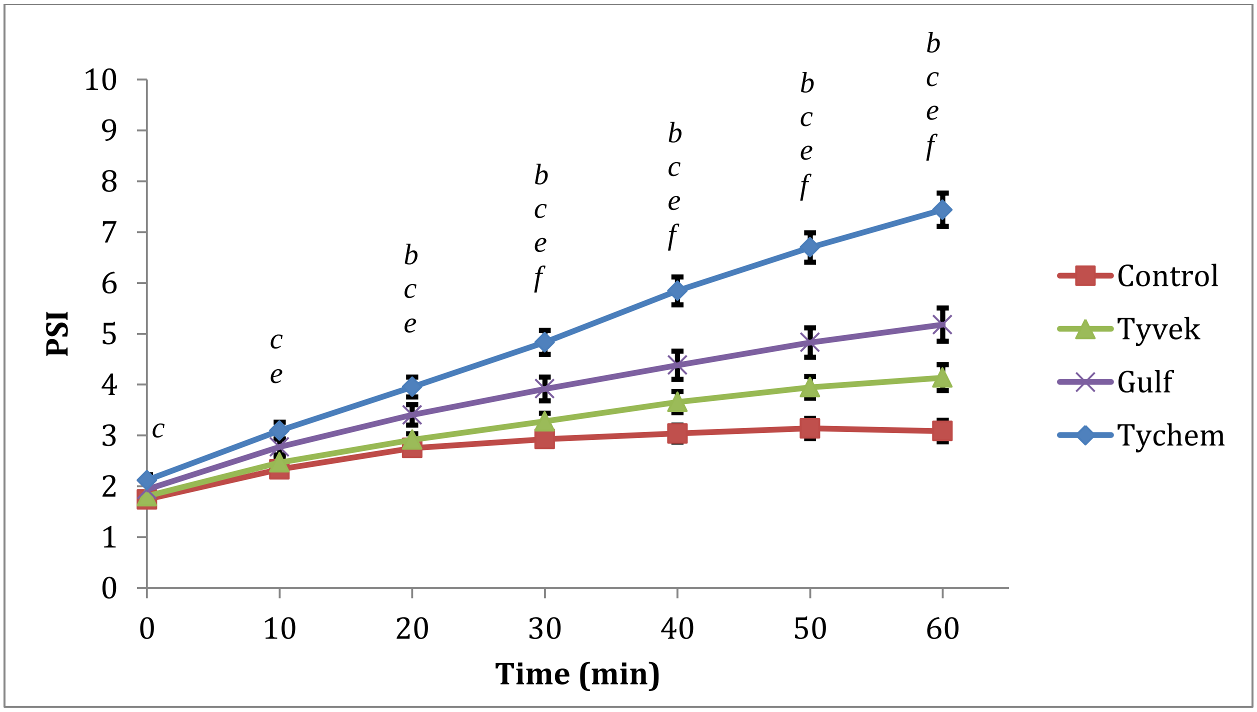
Significance (P <0.05) indicated by *a* (Control vs. Tyvek®), *b* (Control vs. Gulf), *c* (Control vs. Tychem®), *d* (Tyvek® vs. Gulf), *e* (Tyvek® vs. Tychem®) and *f* (Gulf vs. Tychem®)

Figure 5.6 Mean (±SEM) weighted mean skin temperature during 60 minutes of treadmill exercise for Control and three CP coveralls (n=15)



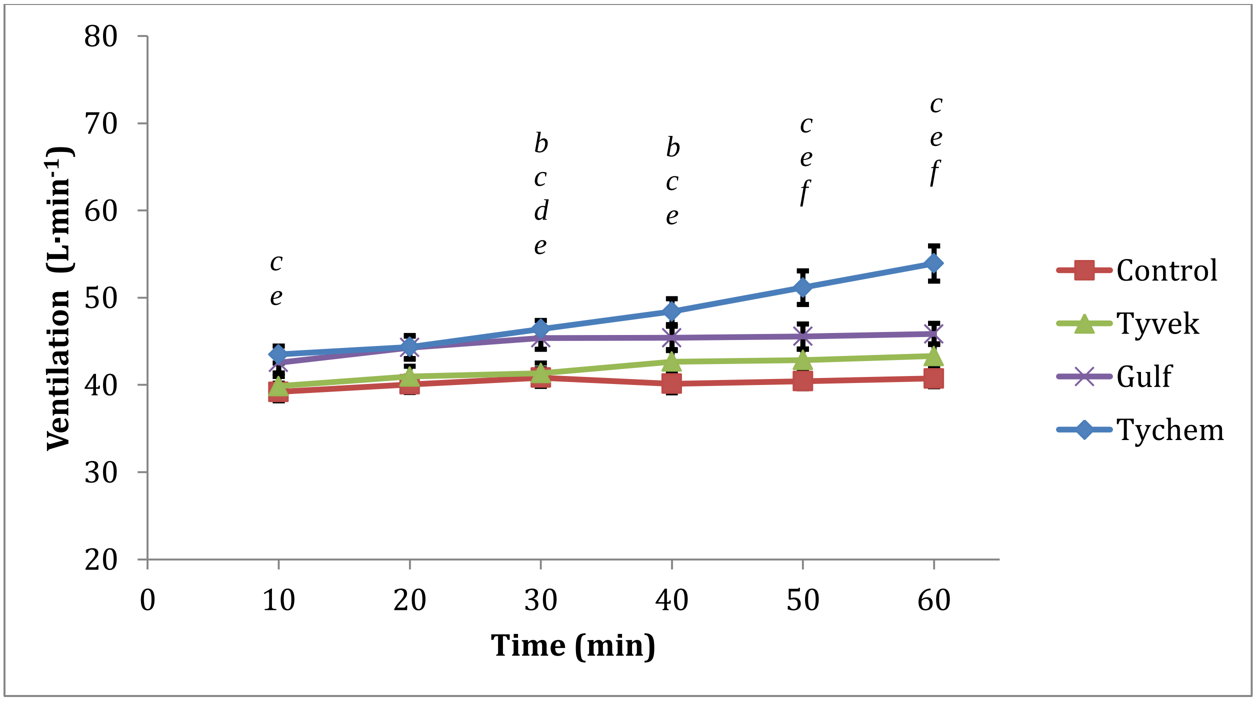
Significance (P <0.05) indicated by *a* (Control vs. Tyvek®), *b* (Control vs. Gulf), *c* (Control vs. Tychem®), *d* (Tyvek® vs. Gulf), *e* (Tyvek® vs. Tychem®) and *f* (Gulf vs. Tychem®)

Figure 5.7 Mean (±SEM) heart rate during 60 minutes of treadmill exercise for Control and three CP coveralls (n=15)



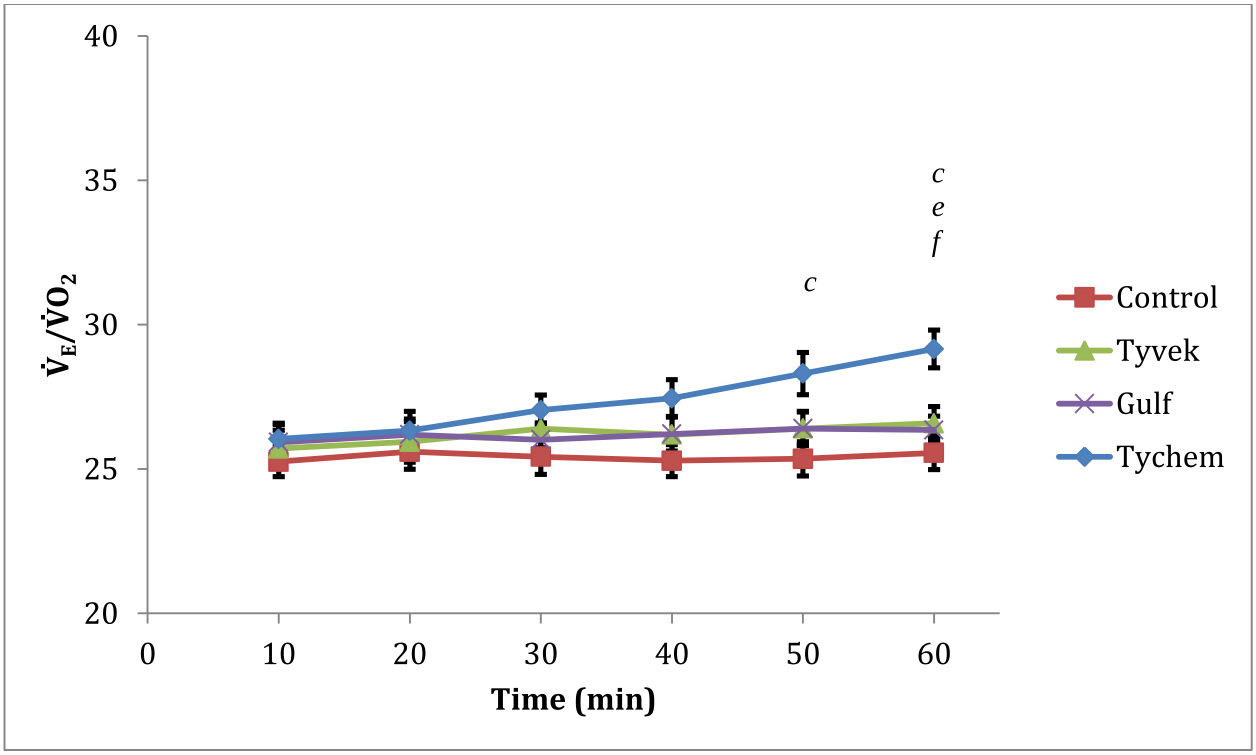
Significance (P <0.05) indicated by *a* (Control vs. Tyvek®), *b* (Control vs. Gulf), *c* (Control vs. Tychem®), *d* (Tyvek® vs. Gulf), *e* (Tyvek® vs. Tychem®) and *f* (Gulf vs. Tychem®)

Figure 5.8 Mean (±SEM) physiological strain index (PSI) during 60 minutes of treadmill exercise for Control and three CP coveralls (n=15)



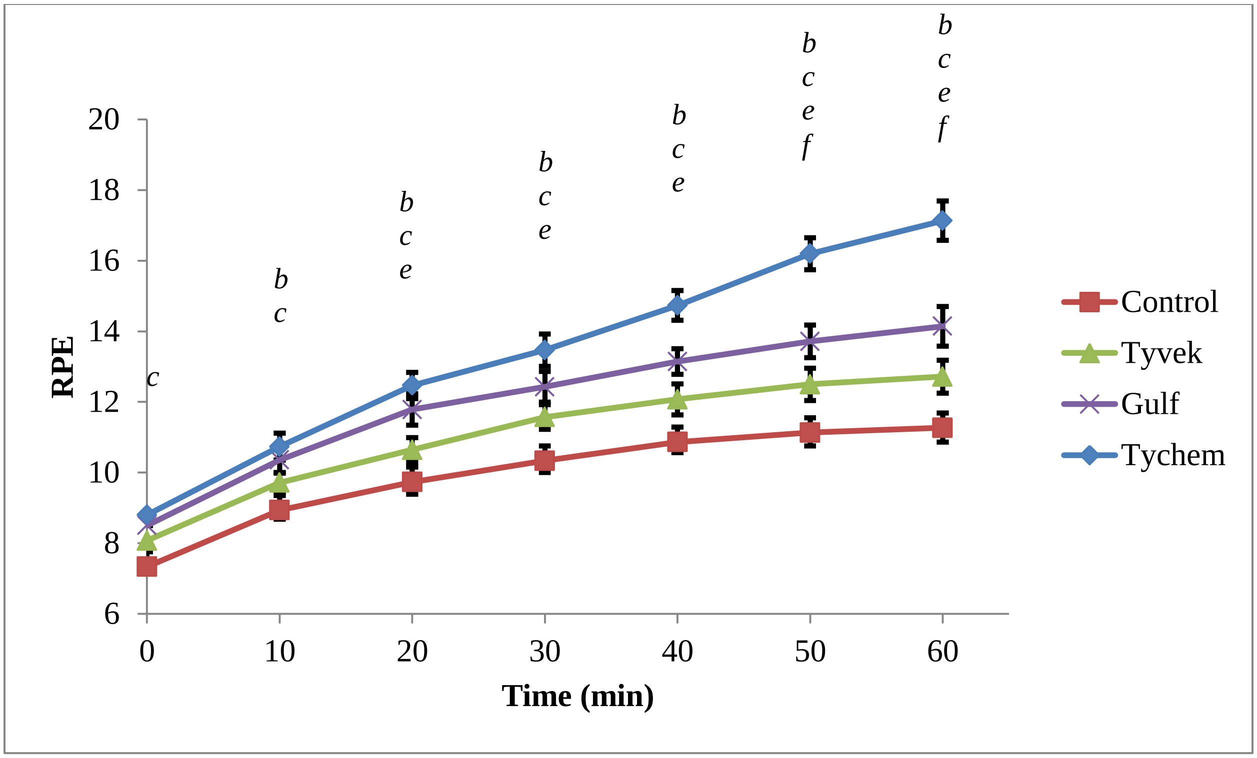
Significance (P <0.05) indicated by *a* (Control vs. Tyvek®), *b* (Control vs. Gulf), *c* (Control vs. Tychem®), *d* (Tyvek® vs. Gulf), *e* (Tyvek® vs. Tychem®) and *f* (Gulf vs. Tychem®)

Figure 5.9 Mean (±SEM) minute ventilation during 60 minutes of treadmill exercise for Control and three CP coveralls (n=15)



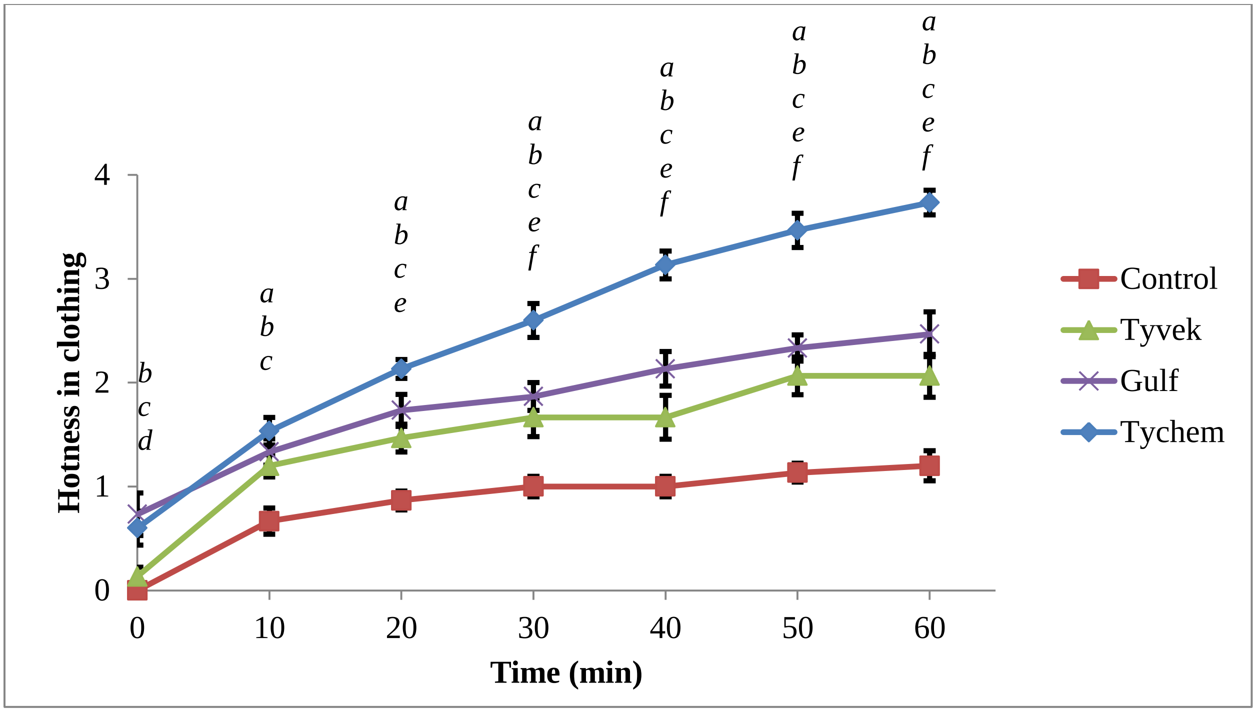
Significance ($P < 0.05$) indicated by *a* (Control vs. Tyvek®), *b* (Control vs. Gulf), *c* (Control vs. Tychem®), *d* (Tyvek® vs. Gulf), *e* (Tyvek® vs. Tychem®) and *f* (Gulf vs. Tychem®)

Figure 5.10 Mean (±SEM) $\dot{V}_E/\dot{V}O_2$ during 60 minutes of treadmill exercise for Control and three CP coveralls (n=15)



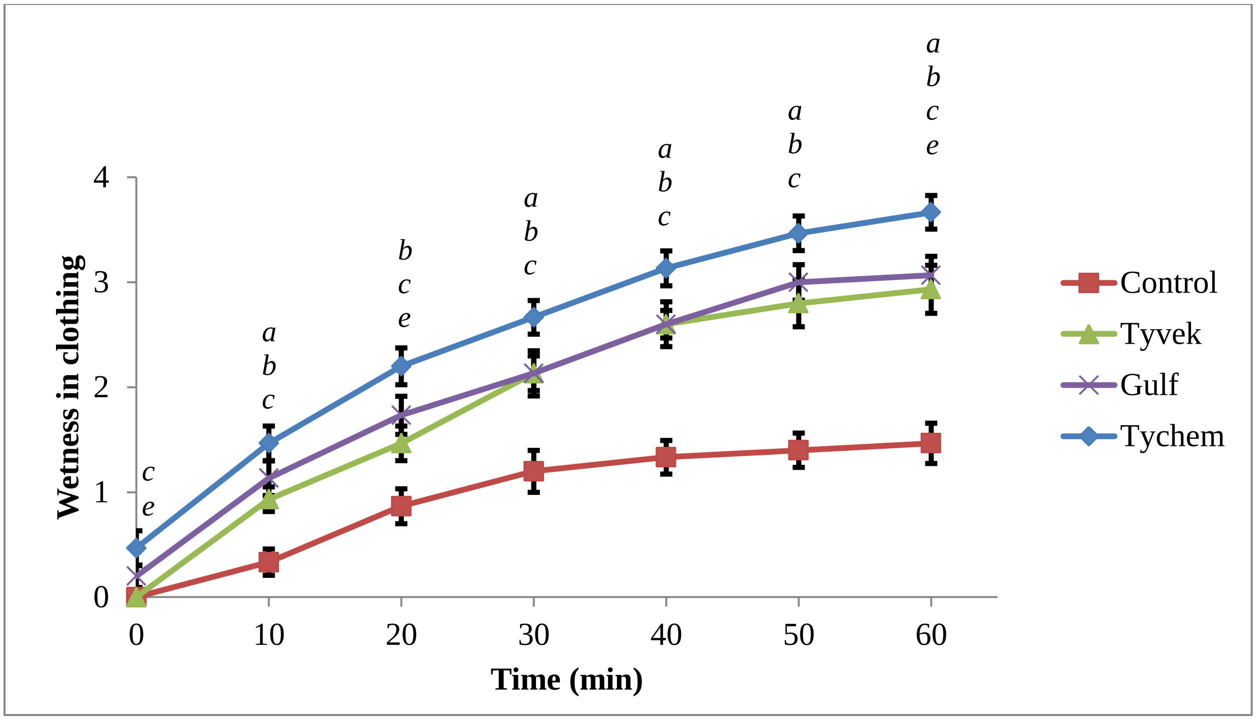
Significance (P <0.05) indicated by *a* (Control vs. Tyvek®), *b* (Control vs. Gulf), *c* (Control vs. Tychem®), *d* (Tyvek® vs. Gulf), *e* (Tyvek® vs. Tychem®) and *f* (Gulf vs. Tychem®)

Figure 5.11 Mean (±SEM) rating of perceived exertion (RPE) during 60 minutes of treadmill exercise for Control and three CP coveralls (n=15)



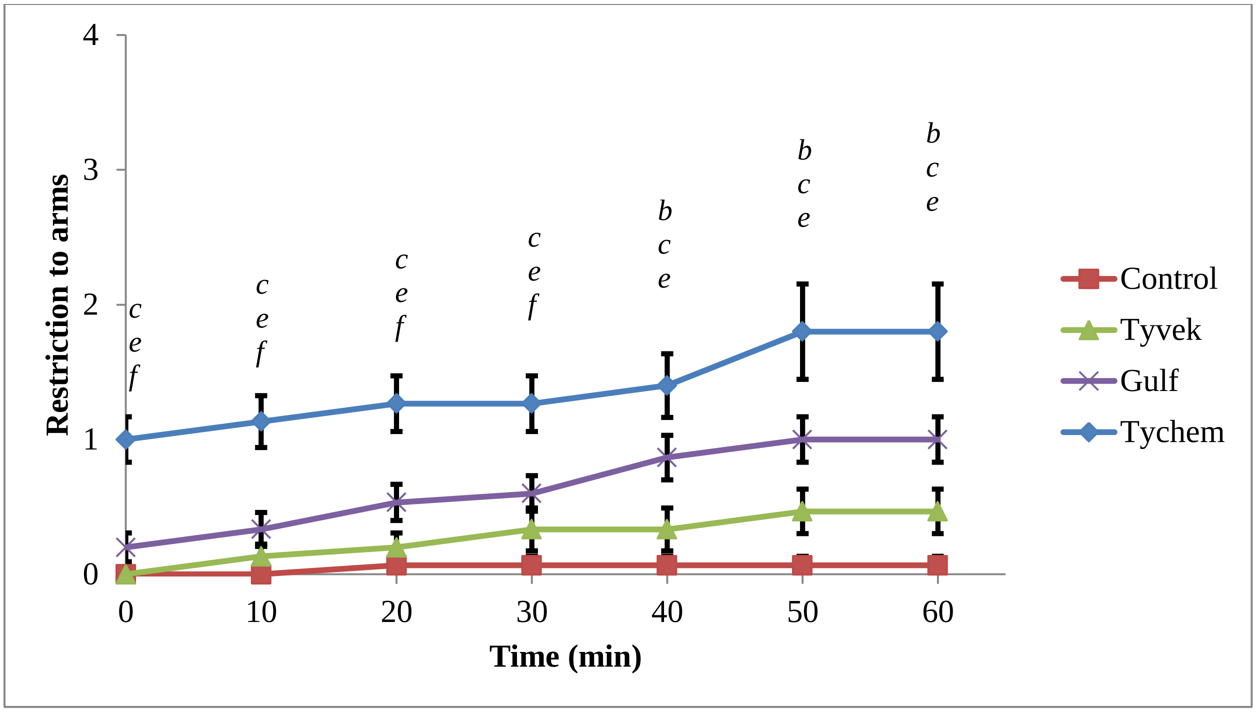
Significance (P <0.05) indicated by *a* (Control vs. Tyvek®), *b* (Control vs. Gulf), *c* (Control vs. Tychem®), *d* (Tyvek® vs. Gulf), *e* (Tyvek® vs. Tychem®) and *f* (Gulf vs. Tychem®)

Figure 5.12 Mean (±SEM) hotness in clothing during 60 minutes of treadmill exercise for Control and three CP coveralls (n=15)



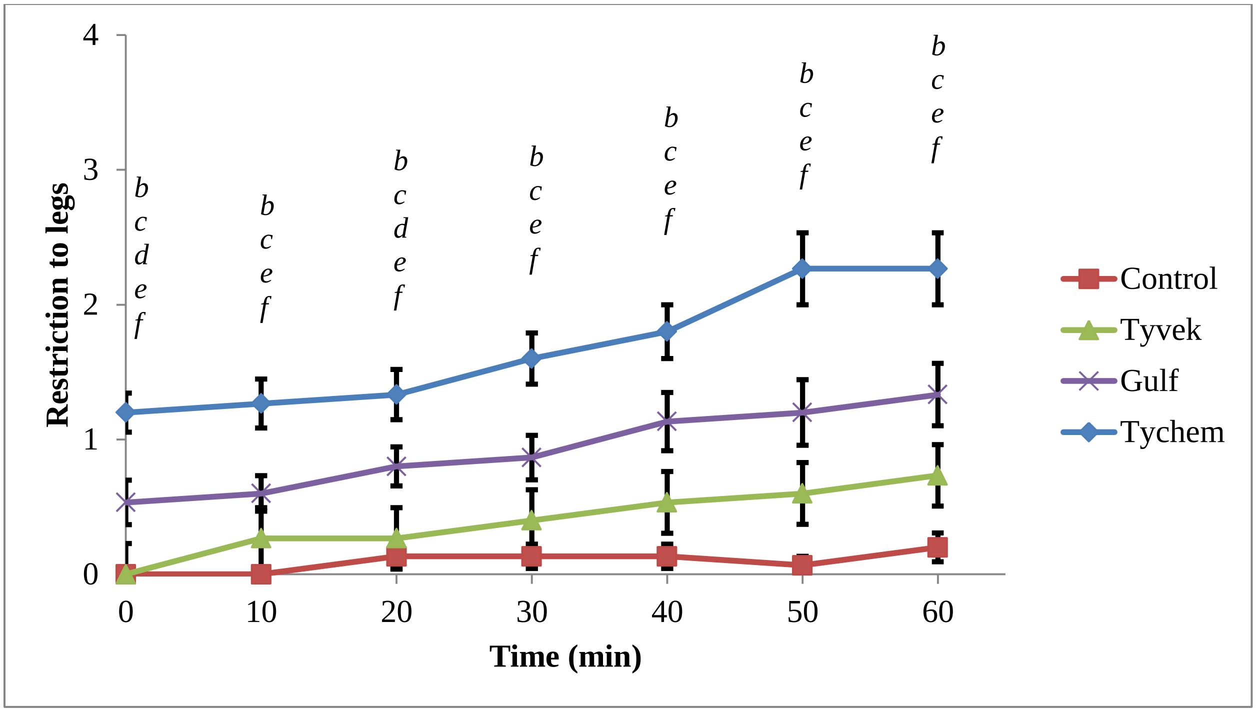
Significance (P <0.05) indicated by *a* (Control vs. Tyvek®), *b* (Control vs. Gulf), *c* (Control vs. Tychem®), *d* (Tyvek® vs. Gulf), *e* (Tyvek® vs. Tychem®) and *f* (Gulf vs. Tychem®)

Figure 5.13 Mean (±SEM) wetness in clothing during 60 minutes of treadmill exercise for Control and three CP coveralls (n=15)



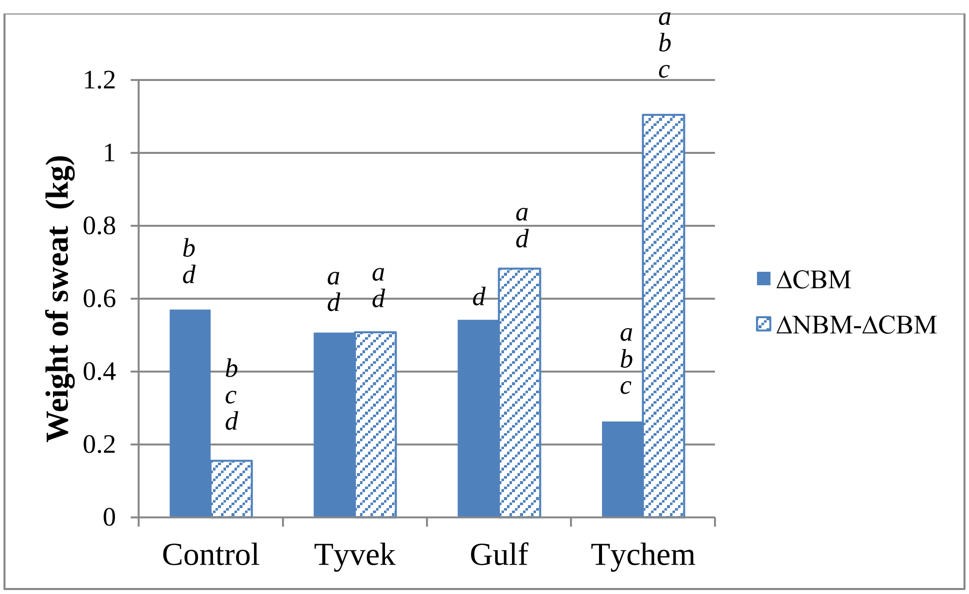
Significance (P <0.05) indicated by *a* (Control vs. Tyvek®), *b* (Control vs. Gulf), *c* (Control vs. Tychem®), *d* (Tyvek® vs. Gulf), *e* (Tyvek® vs. Tychem®) and *f* (Gulf vs. Tychem®)

Figure 5.14 Mean (±SEM) restriction to arms during 60 minutes of treadmill exercise for Control and three CP coveralls (n=15)



Significance (P <0.05) indicated by *a* (Control vs. Tyvek®), *b* (Control vs. Gulf), *c* (Control vs. Tychem®), *d* (Tyvek® vs. Gulf), *e* (Tyvek® vs. Tychem®) and *f* (Gulf vs. Tychem®)

Figure 5.15 Mean (±SEM) restriction to legs during 60 minutes of treadmill exercise for Control and three CP coveralls (n=15)



Significance (P <0.05) indicated by*:*
a = different from the control; *b* = different from Tyvek®;
c = different from Gulf; *d* = different from Tychem®.

Figure 5.16 Mean estimated evaporated sweat (ΔCBM) and accumulated sweat (ΔNBM-ΔCBM)

CHAPTER 6 RELATIONSHIPS BETWEEN FABRIC PROPERTIES AND THERMO-PHYSIOLOGICAL STRAIN AND PHYSICAL BURDEN --THE DEVELOPMENT OF MULTIPLE REGRESSION MODELS

Introduction

In the previous chapters, the thermo-physiological strain and physical burden associated with the selected CP coveralls were assessed through fabric testing, manikin testing and human wear trials. The comprehensive evaluation began with the bench-scale tests using the sweating guarded hot plate and the Kawabata evaluation system to determine the thermal and mechanical characteristics of the materials. Since thermal and moisture transfer properties change once the materials have been constructed into a garment (Holmer, 2004; McCullough, 2005), the thermal and moisture transfer properties were then evaluated on the thermal sweating manikin. Although these two levels of evaluation provide essential physical data, only human testing in controlled laboratory conditions under which the clothing system would be used can provide the necessary data on the physiological burden it imposes (O'Brien et al., 2011). Significant thermal and physical discomfort and strain were found in the human wear trials, particularly, when the CPC consisted of impermeable, stiff and/or thick materials to provide a high level of chemical protection.

The systematic evaluation of the CP coveralls using the multidisciplinary approach provides much more information than any single test method. However, it involves a great amount of time, money and expertise. Modelling the comfort and strain of wearing protective clothing has been a prevalent focus for many researchers in this area (Huizenga, Hui, & Arens, 2001; Malchaire et al., 2001; Pavlinic, Wissler, & Mekjavic, 2011). The predictive models are especially valuable when a large number of scenarios are desired and the cost of testing with human subjects would be prohibitive. Rational models have been developed based on accepted physical laws and physiological principles (Berger & Sari, 2000; Salloum, Ghaddar, & Ghali, 2007; Wan & Fan, 2008). Empirical models have been developed based on relationships between human responses and results from fabric and garment testing (Bishop et al., 1994; O'Brien et al., 2011; Van Gelder, Pranger, Wiesmann, Stachenfeld, & Bogucki, 2008). In this chapter, the relationships between fabric physical properties and the physiological strain and physical burden to the wearer are investigated and regression models of these relationships are presented.

Methods

Dependent variables

Change in core temperature (ΔT_c) and change in weighted mean skin temperature (ΔT_{sk}), before and after the 60 min treadmill exercise, were used as dependent variables to indicate the change of thermo-physiological comfort (strain) in different garment systems (Cortili et al., 1996; Levine et al., 2001; Selkirk & McLellan, 2004).

Average subjective rating of hotness in clothing (HIC) and average wetness in clothing (WIC) during the 60 min experiment were used as dependent variables to indicate the subjective sensations of thermal comfort (Barker & Scruggs, 1996; Marzalek et al., 2009; White et al., 1991).

Average oxygen consumption ($\dot{V}O_{2\text{-}N}$) during the 60 min experiment was used as a dependent variable to indicate the effect of the garment systems on the overall energy expenditure (Bruce-Low, Cotterrell, & Jones, 2007; Cortili et al., 1996). In addition to the differences in energy cost from exercising in the garment systems, the $\dot{V}O_{2\text{-}N}$ value also reflects the different levels of heat generation.

Average rating of perceived exertion (RPE) during the 60 min experiment was used as a dependent variable to indicate the effect of the garment systems on the overall subjective assessment of the difficulty of the work in these different clothing systems (Bruce-Low et al., 2007; Tikuisis et al., 2002; White et al., 1991).

Change in heart rate (ΔHR) and change in the physiological strain index (ΔPSI), before and after the 60 min treadmill exercise, were used as dependent variables to indicate the overall physiological strain imposed during the work in different garment systems (Heled et al., 2004; McLellan, 2008).

Independent variables

In Chapters 3 and 4, differences in fabric and garment physical properties were evaluated using one-way ANOVA analysis. Statistically significant differences were found in the fabric mechanical properties, fabric thickness, fabric R_{ct}, R_{et}, total heat loss (THL) and clothing R_{ct-c} and clothing R_{et-c}. As listed in Table 6.1., these fabric and clothing properties influence the dependent variables (physiological responses) to which they make a contribution based on the fundamental theories of heat and moisture transfer, clothing ergonomics and exercise physiology.

Air permeability was excluded from the independent variables, since Gulf was permeable to air (18.18 $cm^3/cm^2/s$) and Tychem® and Tyvek® (0 and 0.15 $cm^3/cm^2/s$) were essentially impermeable to air. A variable with only two levels does not contribute to a good regression model. The fabric thickness at 0.5gram force (t_{05}) from Kawabata evaluation system (KES) testing was used as an independent variable because when compressed at this low pressure the thickness values give a realistic representation of the materials' actual thickness in use.

Pearson's correlation analysis was used to determine the strength of linear associations between the dependent variables and the related fabric/garment properties (Appendix 8). Among all the tested fabric/garment factors, the two with the highest r values were chosen as the independent variables to be initially entered into the multiple regression analysis of the corresponding dependent variable.

Standard multiple regression

Standard multiple regression as an interpretive analytical tool is used to evaluate the relative importance of the independent variables in explaining variance in a dependent variable. There are some assumptions to be met in a regression analysis: random sample, normal distribution of sample, linear relationship between the dependent and independent variables, and equal variance between the dependent variables and the independent variables (Munro, 2005).

The sample size for this study was relatively small. This is typical of physiological and subjective studies involving the evaluation of garment systems by human subjects. All samples for fabric testing, manikin testing and human wear trials were drawn at random. For all correlation and regression analyses, the data from fabric and garment testing were randomly allocated. It is necessary to randomly allocate one independent measure to each dependent measure since the number of cases for the independent and dependent variables are not the same. This limitation of the data is common to most textile experimental research and not considered to adversely affect the data analysis (Andersson, 1999).

The size of the sample determines how many independent variables can be entered into a regression model. Generally, the bigger the sample size the more factors can be included. Stevens (1996, p.72) recommends that "for social science research, about 15 subjects per predictor are needed for a reliable equation". Tabachnick and Fidell (2007, p. 123) give a formula for calculating sample size requirements, taking into account the number of independent variables that are to be used: $N > 50 + 8m$ (where m = number of independent variables). The sample size of this study ranges from 45 to 60. Therefore, the number of independent variables is controlled for not more than two in each of the regression models.

The assumption of normality of the sample is tested by checking the Normal Probability Plot (P-P) of the regression standardized residual in the SPSS outputs of multiple regression analysis (Pallant, 2007). In the Normal P-P plots for most of the analyses, the points lie in a reasonably straight diagonal line from bottom left to top right, indicating the samples have a close to normal distribution. In the Scatterplots of the standardized residuals of most analyses, the residuals are roughly rectangularly distributed, although in some cases, deviations from the centre was seen because of some extreme values (e.g., the R_{et} value of Tychem®). Appendix 9 shows the output of a standard multiple regression conducted to assess the ability of two independent variables, R_{et} and t_{05} (thickness tested at 5gf/cm^2), to predict the change in core temperature (ΔT_c). The Normal P-P plot and the scatterplot of regression standardized residual are presented at the end of the output.

As mentioned above, Pearson's correlation analysis was tested between every dependent variable and all related independent variables for linear relationships. For all the dependent variables, there were more than two independent variables with significant correlation. Therefore, the two independent variables which had the greatest r values were selected to enter into the regression model.

Equal variance is checked with examination of residuals by searching for visible patterns in the scatter plots. As shown in Appendix 10, a lack of pattern in the data points indicates equal variance. Most of the residuals plotted from the regression analyses appear to be randomly scattered around the horizontal line through zero on the scatter plots.

Multicollinearity exists when the independent variables are highly correlated ($r = 0.7$ and above) (Pallant, 2007). The more strongly correlated the independent variables are, the less predictive is the power that one independent variable has over and above that offered by the other independent variables. Collinearity diagnostics were performed to test for multicollinearity between the independent variables, as shown in Appendix 10. The tolerance statistic was used to measure the strength of the linear relationship among the independent variables. A tolerance value of 1 indicates that the variability of the independent variable was not explained by the other independent variables. A value close to 0 is an indication that an independent variable is highly correlated to the other independent variable and is therefore multilcollinear. In this study, some of the physical textile and garment properties were highly intercorrelated. For example, R_{et} and R_{et-c} are intercorrelated, $r = 0.985$, $p < 0.01$. When multicollinearity is found, the independent variable with the lower r value with the dependent variable (R_{et-c}, $r = 0.789$, $p < 0.01$with ΔT_c) was replaced (marked in red in Appendix 8) with the next independent variable (t_{05}, $r = 0.704$, $p < 0.01$ with ΔT_c). This independent variable must not be multicollinear with R_{et} ($r = 0.605$, $p < 0.01$, between t_{05} and R_{et}). As shown in Appendix 8, the independent variables in red are highly intercorrelated to the other independent variables. The independent variables in bold font for each dependent variable were the two independent variables being entered into the multiple regression analysis.

Results

Predictive regression models

Table 6.2 summarizes the regression models for the physiological measures with two predictors. There were two models that have non-significant predictors. In the results of the predictive model for ΔT_{sk}, the value in the column marked Sig. for t_{05} is 0.294, which was greater than 0.05. This indicates that t_{05} does not have a unique contribution to the equation. This may be due to overlapped contribution with the other predictor, R_{et}. As for ΔPSI, the values in the Sig. column for both predictors, R_{et} and Bending-2HB are greater than 0.05. This is probably due to the small sample size (N = 45). Multiple regression analysis was reconducted for ΔT_{sk} and ΔPSI with one predictor, which is R_{et} in both cases. The standard multiple regression models for ΔT_{sk} and ΔPSI with one predictor are summarized in Table 6.3.

The predictive regression models for the dependent variables are listed below. All predictors are significant at $p < 0.01$.

Model 1:

$$\Delta T_c = 0.021(R_{et}) + 0.234\,(t_{05}) + 0.344$$

Model 2:

$$\Delta T_{sk} = 0.029(R_{et}) + 1.585$$

Model 3:

$$Average\ HIC = 0.378\,(t_{05}) + 0.019\,(R_{et}) + 0.888$$

Model 4:

$$Average\ WIC = 17.532\,(R_{ct}) + 0.014\,(R_{et}) - 0.077$$

Model 5:

$$Average\ \dot{V}O_{2\text{-}N} = 0.838\,(garment\ weight) + 0.706\,(Bending\text{-}2HB) + 19.454$$

Model 6:

$$Average\ RPE = 0.890\,(t_{05}) + 0.038\,(R_{et}) + 9.981$$

Model 7:

$\Delta HR = 0.532 (R_{et}) + 8.805 (t_{05}) + 12.354$

Model 8:

$\Delta PSI = 0.082 (R_{et}) + 1.488$

Discussion

The change in core temperature (ΔT_c) before and after the 60-minute exercise was predicted by the multiple regression equation, Model 1, with R_{et} and t_{05} as the predicting variables. R_{et} is the main predictor with a larger Beta value at 0.590, while t_{05} is found to make a significant additional contribution (Beta = 0.346, $p < 0.01$) to the predictive model. The model in total accounts for 71% of the variation in ΔT_c.

Evaporation of sweat provides a powerful physiological cooling mechanism for humans, taking up 0.58 kcal of heat for each gram of water vaporized (Nunneley, 1989). In a warm environment or during exercise, evaporative heat loss plays a more dominant role than convection or radiation (White & Ronk, 1984). Clothing with higher evaporative resistance (R_{et}) (i.e. the Tychem® coverall) prevents moisture from being released from the garment microclimate. The air in the microclimate quickly becomes humid as a result of sweat. When the air inside the clothing system becomes fully saturated, evaporative cooling is not possible. Heat is stored in the body, resulting in the increase in core temperature.

As reviewed in Chapter 2, thickness is a fundamental fabric characteristics which determines the thermal insulation of the fabric (Saville, 1999). This is shown in Chapter 3, where thickness and thermal insulation (R_{ct}) were found to be highly correlated. R_{ct} is considered to directly reflect the overall heat transfer property of the material, trapped air within the fabric and air layers between fabric layers (Li, 2001). Also, it is a value that combines effects of conduction, convection and radiation. Therefore, although thickness is much easier to measure, in many studies, R_{ct} was used to evaluate thermal comfort of clothing (Gibson, 1993; Holmer, 1988; Xu et al., 2012; Yoo & Barker, 2005). In this study, t_{05} had a higher correlation with ΔT_c than R_{ct}, so it became the second most important factor in predicting ΔT_c.

The t_{05} is also correlated with ΔT_{sk} ($r = 0.411$, $p < 0.01$). However, when it was entered into the two-predictor regression model with R_{et}, no significant unique contribution ($p = 0.294$) was found due to the intercorrelation between t_{05} and R_{et} in predicting ΔT_{sk} (Table 6.2). The R_{ct}, $R_{ct\text{-}c}$ and $R_{et\text{-}c}$ were also found to be highly correlated with the main predictor, R_{et}; therefore the change in mean weighted skin temperature (ΔT_{sk}) was predicted by Model 2 with one predictor, R_{et}. In a clothing system made of fabric with lower R_{et}, more sweat is evaporated, taking away more heat from the skin surface and resulting in a lower skin temperature. It is well documented that water vapour transfer property has been used to investigate the thermal comfort of protective clothing (Barker & Scruggs, 1996; Cowan et al., 1988; Epstein et al., 2013; Lee & Obendorf, 2007). This current study is the first one to connect the fabric R_{et} value with the change in skin temperature.

As important as R_{et} being a predictor for ΔT_{sk}, it only explains 26% of the variation in ΔT_{sk} (Table 6.3). Theories and studies suggest that air permeability is another very important factor (Epstein et al., 2013; Fourt & Hollies, 1970; Gibson, 1993; Shalev et al., 1996). Air impermeable material does not allow the exchange of the warmed (as a result of metabolic heat production) and saturated air in the microclimate with the ambient air of the environment. The temperature and water vapour pressure in the microclimate cannot be brought down as they would be in an air permeable garment. The skin exposed to this microclimate cannot experience effective convective or evaporative cooling. Skin temperature rises as heat is generated continuously. Due to the limitation of the variety of air permeabilities included in the study, it was not possible to use air permeability as a predictor in the regression models.

Similar to the objective change of body temperatures, the subjective ratings of thermal comfort sensations, average HIC and average WIC were also predicted by R_{et} and t_{05} (or R_{ct}). This was not surprising since it has been revealed in Chapter 5 that the subjective thermal evaluations were correlated with the objective physiological responses (Table 5.3) in the wear trials. Previous studies found that the use of CPC increases the perception of thermal stress including subjective ratings of skin wetness and temperature in clothing (Marzalek et al., 2009; White et al., 1991). A highly significant relationship was found between the perceived wetness and the measured water vapour pressure on the skin surface

(Holmer, Nilsson, et al., 1992). No studies using models that predict thermal comfort perceptions based on measurable fabric properties were found. Model 3, with t_{05} and R_{et} as the predictors, accounts for 67% of the variation in the average HIC. Model 4, with R_{ct} and R_{et} as the predicting variables, explains 54% of the variation in the average WIC.

It is important to recognize that the sensory thermal comfort performance of clothing involves a large number of complex and inter-related factors in addition to the heat and moisture transfer properties of the material (Li, 2001). As reviewed in Chapter 2, the wickability of fabric may have a significant effect on the skin wetness perception. The wetness in the microclimate of a garment made of fabric with one-way transfer ability and liquid moisture management capacity was significantly lower, because the liquid sweat was quickly transferred from the skin to the surface of the garment (Guo et al., 2008). The sensory warm or cool feel of fabric is related to its intrinsic properties, such as specific heat, thermal conductivity and specific contact area (Fourt & Hollies, 1970). A smoother material with increased contact area usually provides a cooler feel (Barker & Scruggs, 1996). For clothing worn next to skin, the properties mentioned above are very important to the subjective thermal sensations. In this study, the same control garments were worn in all the conditions, the effects of moisture management properties and cool/warm touch are not the focus of this research.

The average oxygen consumption ($\dot{V}O_{2\text{-}N}$) during the 60-minute exercise is predicted by the multiple regression equation, Model 5, with garment weight and Bending-2HB as the predicting variables. Garment weight is the main predictor with a relatively larger Beta value at 0.418, while Bending-2HB is found to make a significant additional contribution (Beta = 0.370, $p < 0.01$) to the predictive model. The model in total accounts for 31% of the variation in average $\dot{V}O_{2\text{-}N}$. It is documented that higher oxygen consumption is associated with heavier garment weight (Dorman & Havenith, 2009; Rissanen et al., 2008). As discussed in Chapter 5, fabric mechanical charactersitics, such as stiffness, inflexibility, bulkiness and friction between fabric layers, are considered to contribute to the movement restriction to the wearer. Model 5 is the first predictive model which includes the effects of both garment weight and a mechanical parameter. Bending-2HB is the recovery ability of fabric after being bent. A higher Bending-2HB value means harder to recover or lower recovery ability. When a person is working in a garment and the garment is made of fabric with low bending recovery, the deformations of the fabric caused by the wearer's first movements resist the unbending which may be required for the next movements and create burden on the wearer as they try to work in the garment. More energy is needed for the person to continue working in this garment. It is safe to assume that similar phenomena exist when the fabric is stretched, sheared or compressed during movement. As listed in Appendix 8, average $\dot{V}O_{2\text{-}N}$ is correlated with tensile, shearing and compression behaviours of the fabric. In future studies, when the sample size is big enough for more independent variables to be included, average $\dot{V}O_{2\text{-}N}$ is expected to be predicted better with a multiple regression model that considers more factors and has a higher R^2.

The average rating of perceived exertion (RPE) during the 60 min exercise and the change in heart rate (ΔHR) were predicted by the multiple regression equations, Model 6 and Model 7, with t_{05} and R_{et} as the predicting variables. The models accounts for 49% and 61% of the variation in average RPE and ΔHR, respectively (Table 6.2). RPE and HR are correlated physiological measures which reflect the overall strain or level of difficulty in doing work (Borg, 1982). In many studies, RPE and HR were monitored to investigate the physiological effects of protective clothing, breathing apparatus, work load and environmental conditions (Bruce-Low et al., 2007; McLellan, 1993, 2008; Tikuisis et al., 2002; White et al., 1991). Some of the findings of the effects of protective clothing included the following: impermeable encapsulated ensembles caused worse cardiovascular strain than permeable ones (Reneau et al., 1997); opening of zippered vents in the clothing reduced the thermal and cardiovascular strain (McLellan, 2008); and thermal strain was negatively affected with different cooling method in CPC (Vernieuw et al., 2007). This study has for the first time quantified the contributions to the average RPE and ΔHR using two fabric physical properties, t_{05} and R_{et}, while the work intensity and environmental conditions are controlled.

In the two-predictor regression model for ΔPSI highlighted in Table 6.2, the predictors, R_{et} and Bending-2HB were not found to make a significant unique contribution ($p > 0.05$) to the equation even though they were both correlated to the independent variable ΔPSI in the Pearson's correlation analyses. The reason for the model failed to show significance is very likely because of the small sample size, N = 45. Therefore, in Model 8, the predictor that has the highest correlation coefficient with ΔPSI, R_{et} was entered into the regression analysis. The results (Table 6.3) show that R_{et} was a significant predictor (Beta = 0.776, $p < 0.01$) in the this one-predictor model. Mclellan (2008) found that PSI in a two-piece CP ensemble was significantly reduced when the zippered vents were opened. The opening of the vents changed the heat and moisture exchange between the microclimate and the environment. PSI, after all, was determined by the level of heat storage and difficulty of work. Garment openings, vents, $R_{ct,}$ R_{et}, garment weight and fabric mechanical properties all could have a contribution to PSI. However, in the current study, the most influential factor was determined to be R_{et} and it explains 60% of the variance in ΔPSI.

In summary, R_{et} was found to be the most important fabric predictor in this research. It influenced all the dependent variables expect for oxygen consumption. As fabric evaporative resistance increased, so did change in core temperature, change in skin temperature, change in heart rate, change in physiological strain index, average hotness in clothing, average wetness in clothing and average rating of perceived exertion. Thickness was the next most important predictor of thermo-physiological strain exercising in selected CP coveralls. Garment weight and fabric mechanical properties contribute to the oxygen consumption when exercising in these garment systems.

The models above allow the prediction of physiological strain and physical burden in similar CP coveralls based on fabric thermal and mechanical properties. For example, according to Model 1, the Proshield® and Cold coveralls are predicted to have changes in core temperature at 0.6°C and 1.5°C respectively after the same 60 minutes exercise protocol. This indicates that working in a Proshield® coverall will result in a core temperature that is slightly higher than in Control and slightly lower than in Tyvek® due to its lower thickness and R_{et}. The thermal strain in Cold is predicted to be higher than in Gulf due to the significantly greater thickness but lower than in Tychem® due to its significantly lower R_{et}.

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Table 6.1 Fabric and garment properties contributing to different dependent variables

Dependent variables	Related fabric and garment properties
ΔT_c, ΔT_{sk}, Average HIC, Average WIC	R_{ct}, R_{et}, THL, $R_{ct\text{-}c}$, $R_{et\text{-}c}$, and t_{05}
$\dot{V}O_{2\text{-}N}$	Tensile-LT, Tensile-WT, Tensile-RT, Bending-B, Bending-2HB, Shearing-G, Shearing-2HG, Shearing-2HG5, Compression-LC, Compression-WC, Compression-RC, Surface-MIU, Surface-MMD, Surface-SMD and garment weight
Average RPE, ΔHR, ΔPSI	R_{ct}, R_{et}, THL, $R_{ct\text{-}c}$, $R_{et\text{-}c}$, t_{05}, Tensile-LT, Tensile-WT, Tensile-RT, Bending-B, Bending-2HB, Shearing-G, Shearing-2HG, Shearing-2HG5, Compression-LC, Compression-WC, Compression-RC, Surface-MIU, Surface-MMD, Surface-SMD and garment weight

Table 6.2 Summary of standard multiple regression models with two predictors for the physiological measures

Physiological variables	Predictor variables	Unstandardized coefficients B	Unstandardized coefficients Std. Error	Standardized coefficients Beta	t	Sig.	df	F	R^2	Adjusted R^2
ΔT_c	(constant)	0.344	0.070		4.934	0.000	2/57	71.872	0.716	0.706
	R_{et}	0.021	0.003	0.590	6.661	0.000				
	t_{05}	0.234	0.060	0.346	3.908	0.000				
ΔT_{sk}	(constant)	1.511	0.173		8.736	0.000	2/57	11.574	0.289	0.264
	R_{et}	0.024	0.008	0.434	3.097	0.003				
	t_{05}	0.157	0.148	0.148	1.058	0.294				
Average HIC	(constant)	0.888	0.089		9.934	0.000	2/57	59.718	0.677	0.666
	t_{05}	0.378	0.077	0.466	4.927	0.000				
	R_{et}	0.019	0.004	0.453	4.787	0.000				
Average WIC	(constant)	-0.077	0.296		-0.262	0.794	2/57	34.889	0.550	0.535
	R_{ct}	17.532	3.470	0.532	5.053	0.000				
	R_{et}	0.014	0.005	0.306	2.905	0.005				
Average $\dot{V}O_{2\text{-}N}$	(constant)	19.454	0.708		27.480	0.000	2/42	10.977	0.343	0.312
	Garment weight	0.838	0.252	0.418	3.323	0.002				
	Bending-2HB	0.706	0.240	0.370	2.940	0.005				
Average RPE	(constant)	9.981	0.277		36.027	0.000	2/57	28.983	0.504	0.487
	t_{05}	0.890	0.239	0.439	3.722	0.000				
	R_{et}	0.038	0.013	0.351	2.979	0.004				
ΔHR	(constant)	12.354	2.538		4.867	0.000	2/57	47.348	0.624	0.611
	R_{et}	0.532	0.117	0.467	4.554	0.000				
	t_{05}	8.805	2.190	0.413	4.020	0.000				
ΔPSI	(constant)	1.465	0.260		5.625	0.000	2/42	31.961	0.603	0.585
	R_{et}	0.057	0.037	0.534	1.520	0.136				
	Bending-2HB	0.481	0.676	0.250	0.711	0.481				

Table 6.3 Summary of standard multiple regression models with one predictor for ΔT_{sk} and ΔPSI

Physiological variables	Predictor variables	Unstandardized coefficients		Standardized coefficients			df	F	R^2	Adjusted R^2
		B	Std. Error	Beta	t	Sig.				
ΔT_{sk}	(constant)	1.585	0.158		10.027	0.000	1/58	21.982	0.275	0.262
	R_{et}	0.029	0.006	0.524	4.688	0.000				
ΔPSI	(constant)	1.488	0.220		6.749	0.000	1/58	87.897	0.602	0.596
	R_{et}	0.082	0.009	0.776	9.375	0.000				

CHAPTER 7 CONCLUSIONS

Summary of the Studies

The purpose of this research was to develop regression models for explaining and predicting the physiological strain and physical burden in the selected chemical protective clothing (CPC) through characterization of the comfort-related fabric and/or garment properties. Four studies were designed to accomplish this purpose.

In the first study, the thermal and mechanical properties of six CPC materials were measured and the thermal and physical comfort of these CPC were characterized. The thermal insulation and evaporative resistance of the CPC materials were determined at fabric-level using a standard sweating guarded hotplate. The total heat loss value was used to rank the thermal comfort level of wearing the CPC made of these materials. Fabric mechanical properties at low stress levels were measure by the Kawabata Evaluation System (KES). Overall mechanical performance of the materials was evaluated by combining the fabric mass, tensile, bending, shearing, surface contour and friction properties into a multi-axis radar graph.

The purpose of the second study was to determine the clothing ergonomics and the heat and moisture transfer properties of the selected twelve CP coveralls and to assess restrictions to movement and thermal discomfort of the selected coveralls at the garment level. Three dimensional scanning and Geomagic® software were used to determine the average air gap size and microclimate volume of each coverall. The thermal insulation and evaporative resistance of the twelve CP coveralls were determined using a thermal sweating manikin. The results were compared for the different material types and garment sizes. The effects of material type and garment size on thermal and physical comfort provided by the CP garments were discussed within the context of full-scale garment testing.

The third study consisted of controlled human wear trials that determined the physiological responses and subjective comfort perceptions of wearing a control garment system and three CPC ensembles during moderate treadmill exercise in temperate environmental conditions. The thermo-physiological strain and physical burden was described and discussed in detail, taking oxygen consumption, core temperature, skin temperature, heart rate, physiological strain index, subjective rating of hotness in clothing, wetness in clothing, restrictions to arms, restriction to legs and rating of perceived exertion into consideration.

In the fourth study, statistical regression models were developed based on the relationships between the human responses and the results from the fabric and garment tests. Eight physiological responses during the wear trials were selected as the dependent variables, including change in core temperature (ΔT_c), change in weighted mean skin temperature (ΔT_{sk}), average subjective rating of hotness in clothing (HIC), average wetness in clothing (WIC), average oxygen consumption ($\dot{V}O_{2\text{-}N}$), average rating of perceived exertion (RPE), change in heart rate (ΔHR) and change in the physiological strain index (ΔPSI). The corresponding independent variables were determined based on the results of Pearson's correlation analyses and multicollinearity tests. Eight predictive models were established using standard multiple regression analyses.

Summary of Findings

This dissertation began by suggesting that the effects of chemical protective clothing on wearer's thermo-physiological strain and physical burden could not be understood thoroughly or predicted without a comprehensive and holistic investigation. The findings of the four studies comprising this research are summarized here by revisiting the hypotheses presented in the introduction.

The six CPC fabrics showed significant differences in low-stress mechanical and surface properties obtained from the KES tests. Five mechanical parameters, including tensile linearity (LT), bending rigidity (B), shearing stiffness (G), surface roughness (SMD), and fabric weight (W), were analyzed and summarized into a multi-axis radar graph (Figure 3.10). According to this radar graph, the Tychem® fabric had much higher bending rigidity and shearing stiffness than all of the other materials, therefore the physical burden to the wearer in the Tychem® garment was expected to be the greatest. Tyvek® and Proshield® were determined to impair physical comfort the least, since the pentagon areas plotted for these materials in the radar graph were the smallest. The multi-layer materials, Cold, Gulf and Prototype, had relatively higher fabric weight and surface roughness, were predicted to impair work efficiency and physical comfort because of these properties. The thermal comfort performance of five CPC fabrics (Prototype was excluded for lack of material) was predicted based on the total heat loss values. Proshield® was predicted to be the most comfortable and Cold, the least comfortable. Tyvek®, Gulf and Tychem® were assessed as more thermally comfortable than Cold but less comfortable than Proshield®. It was not possible to differentiate the thermal comfort levels provided by Tyvek®, Gulf and Tychem® garments based on the bench-scale testing.

In the 3-D garment ergonomic analyses of the twelve CP coveralls, no significant effects of garment size or fabric type were found for the average air gap size (AAGS) or microclimate volume (V_m). The p values of the ANOVA analyses of the effects of fabric type on AAGS and V_m were fairly close to 0.05 ($p = 0.066$ and 0.056). This indicated that the reason for no significant differences was very likely due to the small sample size. Garment size was not a significant factor influencing AAGS and V_m. As garment size increases, the AAGS or V_m may not increase significantly. This is a result of the combined effects of fabric mechanical properties, unit mass and drape characteristics (Mah & Song, 2010; Yu et al., 2012). The full-scale clothing thermal insulation (R_{ct-c}) and evaporative resistance (R_{et-c}) values determined from the thermal sweating manikin tests generally were found to agree with the results from the sweating guarded hotplate tests. The multi-layer coveralls, Gulf and Cold had higher R_{ct-c} than Tyvek® and Tychem®. The full-scale R_{et-c} was found to be highly correlated to the bench scale R_{et} from the sweating guarded hotplate testing, $R^2 = 0.970$, $p \leq 0.01$. Tychem® had the highest R_{et-c}, followed by the heaviest coverall, Cold. The lowest R_{et-c} was found with Gulf and Tyvek® and they were not significantly different from each other. It is predicted that at rest or in a cool environment, heat dissipation from Tyvek® and Tychem® coveralls would be more effective than from Gulf and Cold coveralls because of the difference in thermal insulation. When the ambient temperature is close to or higher than skin temperature or the wearer is performing work tasks, evaporative cooling becomes the dominant cooling avenue (White & Ronk, 1984). The Tychem® coverall with the highest R_{et-c} would be expected to impair thermal comfort significantly more than the other coveralls. Another key finding of the sweating manikin tests was that garment size was not an influential factor for heat and moisture transfer through the garment system. This is due to the fact that AAGS and V_m did not increase significantly when garment size increased. Also, the air gap size of these garments had already exceeded the critical air gap size at which convection is initiated (Lotens & Havenith, 1991).

The objective and subjective assessment of thermo-physiological and physical comfort was successfully quantified for the selected CP garment systems during the controlled human trials. Of the three CP coveralls tested in the human wear trials, the Tychem® provides the greatest chemical protection. This garment showed the highest thermo-physiological strain and physical burden on the wearer with the highest results for all the tested human responses. Gulf was also found to impair thermo-physiological and physical comfort significantly in comparison to the Control as the significance demonstrated in the results of oxygen consumption ($\dot{V}O_2$), core temperature (T_c), mean weighted skin temperature (T_{sk}), heart rate (HR), physiological strain index (PSI), rating of perceived exertion (RPE), hotness in clothing (HIC), wetness in clothing (WIC), restriction to arms (RTA) and restriction to leg (RTL). Tyvek® was identified as the most comfortable CPC among the three coveralls, which only showed slightly higher thermal discomfort than the Control with greater T_{sk}, HIC and WIC. There was no significant physical burden from exercising in Tyvek® coverall. One additional finding of the human trials was that the subjective rating responses were successfully correlated to the objective physiological results, indicating that the subjective rating scales used were valid.

Significant positive linear relationships were found between the thermal properties of the CPC fabrics (i.e., R_{ct}, R_{et}, total heat loss and fabric thickness) and the physiological strain (i.e., change in core and skin temperature, average hotness and wetness in clothing) determined in human trials. Significant linear relationships were found between mechanical properties (fourteen properties determined in KES tests, Appendix 10) of the CPC fabrics and physical burden (i.e., average oxygen consumption) determined in human trials. Change in heart rate, rating of perceived exertion and physiological strain index are measures that reflect both thermal and physical strain (Heled et al., 2004; Marzalek et al., 2009; Tikuisis et al., 2002; White et al., 1991). Significant linear relationships were found between these three measures and all of the fabric thermal properties and most of the fabric mechanical properties. Among all the properties, R_{et} was found to be the most influential fabric predictor of comfort.

Significant positive linear relationships were found between the thermal properties of the CP garments (i.e., R_{ct-c} and R_{et-c}) and the physiological strain (i.e., change in core and skin temperature, average hotness and wetness in clothing) determined in human trials. Significant positive linear relationships were found between garment weight and physical burden (i.e., average oxygen consumption). Significant positive linear relationships were also found between garment weight and average heart rate, rating of perceived exertion and physiological strain index. Among all the garment properties, clothing evaporative resistance (R_{et-c}) was found to be the most important predictor. It influenced all the dependent variables. However, it was also found that the r values between R_{et-c} and the dependent variables were lower than those of fabric evaporative resistance (R_{et}). R_{et-c} was a predictor of thermo-physiological strain only because it was highly related with R_{et}.

Conclusions

The use of a systematic and holistic framework provided a comprehensive and interdisciplinary approach to the study of the effects of chemical protective clothing on the wearer's thermo-physiological and physical comfort, where the influence of each variable involved and the interactions of those variables could be evaluated and incorporated into the developed models.

The chemical protective clothing systems increased the metabolic cost of performing the same treadmill exercise by adding weight and/or by restricting movement. This was shown in the predictive model for average oxygen consumption ($\dot{V}O_{2-N}$), where garment weight and bending recovery were the two significant predictors. The bench-scale KES testing provided results of sixteen individual mechanical properties of the CPC materials. Rankings of the materials can be made on their level of stretchiness, rigidity to bending, stiffness to shearing, compressional deformation resistance, and surface roughness according to the individual parameters. Overall ranking of physical burden in these CPC was predicted by incorporating five mechanical properties into a multi-axis radar graph. However, it was impossible to predict the magnitude of the physical burden in each CPC with the bench-scale results alone.

As absorbent layers and impermeability are the two ways to achieve chemical protection, thickness and moisture transfer property are the two main factors influencing the thermal comfort of CPC (Slater, 1996). This was shown in the predictive models for change in body temperature (ΔT_c and ΔT_{sk}), average subjective hotness, wetness and exertion perceptions (average HIC, WIC and RPE), and change in heart rate and physiological strain index (ΔHR and ΔPSI), where evaporative resistance and thickness were the two significant predictors. The bench-scale fabric test results for thermal insulation (R_{ct}) and evaporative resistance (R_{et}) indicated which fabrics would prevent more dry or evaporative heat loss. The calculated total heat loss (THL) provided a means of predicting the thermal comfort ranking in the tested CPC. However, with the bench-scale testing alone, it was not possible to translate the differences in R_{ct} and R_{et} into the differences in actual physiological responses. For example, the THL fabric test results for Proshield® suggest that this garment will be more thermally comfortable than all the other coveralls. However, the magnitude of the difference is not known. In addition, it is not known whether wearing Proshield® garment will be as comfortable as when no coverall is worn. Another limitation with using THL to predict thermal comfort is that THL tended to underestimate the contribution of evaporative heat loss and overestimate the contribution of dry heat loss. This is exaggerated while exercising or high environmental temperature is involved. According to the THL results of Tychem® and Gulf fabrics, there was no difference predicted between them for thermal comfort. In the wear trials, however, these two coveralls were found to be significantly different, with Tychem® ensemble impairing the thermal comfort more than Gulf.

Although many studies suggest that the sweating manikin is a more advanced tool than the sweating hotplate for the evaluation of thermal comfort, the advantages of determination heat and moisture transfer properties in full-scale testing were not recognized in this research. No garment-level thermal property was found to be more powerful in predicting thermo-physiological strain than the fabric-level factors.

Contributions of This Research

No research was found that studied the relationships between mechanical properties of fabrics and physical burden in the garment. Therefore, studying the mechanical properties of the CPC materials and relating them with the physical burden in the CPC as part of this research has contributed to a better understanding of physical burden in CPC and the influential material properties.

This research has also extended the bench-scale and full-scale thermal comfort evaluations of garments by comparing and relating the results from both methods. A better understanding on the advantages and disadvantages of the sweating hotplate and sweating manikin has been obtained, especially when working with chemical protective clothing with extra thickness, impermeability and restricted garment openings.

This research has led to a better understanding of the influence of chemical protective clothing on human physiology during exercise in these garments. It has also established a testing protocol that is suitable for the evaluation of chemical protective ensembles.

Research on developing predictive models of comfort and work performance in protective clothing is very limited (Bishop et al., 1994; O'Brien et al., 2011; Van Gelder et al., 2008). Developing such models requires a multidisciplinary perspective, incorporating the fields of textile and clothing science, ergonomics, work physiology and statistics. This research has contributed to the area of clothing comfort prediction and modelling.

The models developed enable textile researchers to predict the CPC effects on worker performance and comfort even prior to garment construction or task assignment. The understanding gained from these studies ultimately facilitates development of more comfortable and less impeding garments. It may also be possible to adapt the systematic approaches outlined in this research when studying the effects of other types of personal protective equipment or components.

Recommendations for Future Research

As stated in the limitations, more garment types and more replications can be investigated to improve the predictive models by including more predictors and increasing the statistical power. The CPC can be chosen or constructed carefully to cover a variety of air permeability levels, so that the influence of ventilation on thermal comfort can be investigated and incorporated into the models. More replications can be tested in the 3-D ergonomic analyses and thermal sweating manikin tests to enable the two-way ANOVA analysis of the individual and interaction effects of garment type and size on air gap size, microclimate volume and clothing thermal and moisture transfer properties.

Sweat-wetting was not investigated but it is known to seriously reduce clothing insulation value and thus improve the heat transfer from the skin to the environment. However, sweat-wetting tends to diminish evaporative cooling (Nunneley, 1989). Craig and Moffitt (1974) found that the cooling effect per gram of water evaporated declined progressively as the clothing wetness increased. Fabric mechanical properties may be changed when the clothing is wetted, therefore, the restriction to movement may also be changed. Future research could investigate the influence of clothing wetness on wearer's thermal and physical comfort.

Body movement could increase heat exchange through clothing by pumping microclimate air into the ambient air. This "pumping" effect means that the actual insulation and vapour resistance characteristics of an ensemble may be much lower than the values measured on a static manikin (Nunneley, 1989). In this research, the sealed clothing prevented the pumping effect, especially in the impermeable ensembles. In the future, inter-related pumping effects of clothing systems with safe ventilation designs could be investigated during task phases while different motions are performed (e.g., resting and walking).

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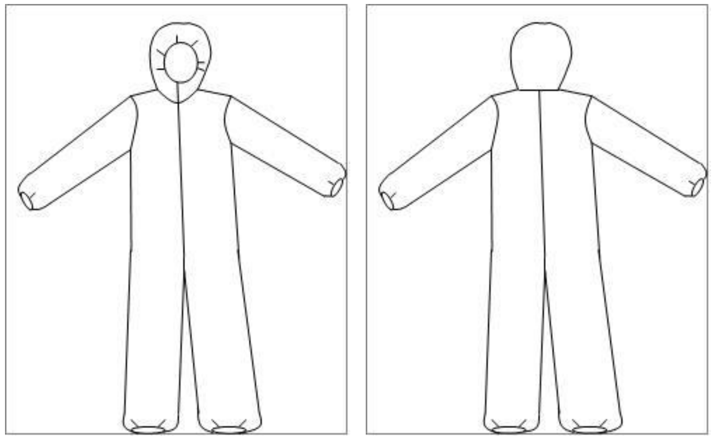
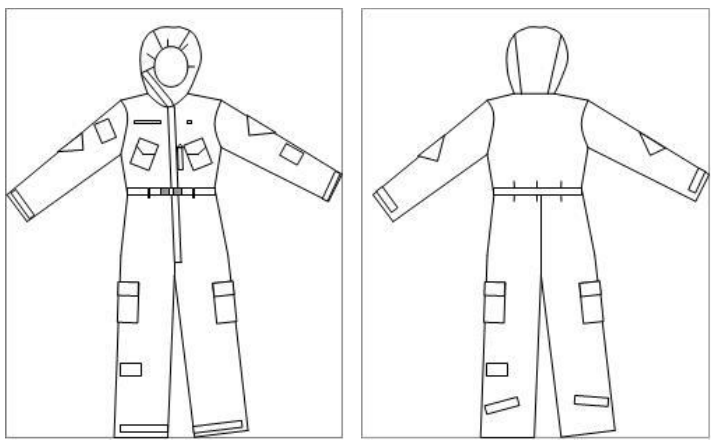
APPENDICES

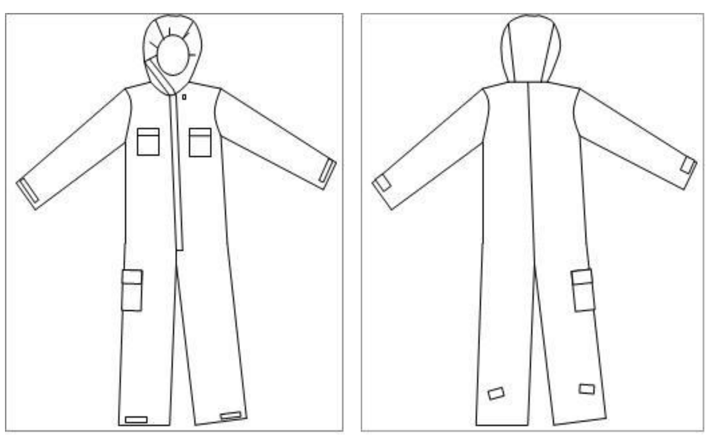
Appendix 1. Sketches of garment design



(a) front and back view of Proshield®, Tyvek® and Tychem®



(b) front and back view of Gulf;



(c) front and back view of Cold

Appendix 2. Fabric thermal insulation (R_{ct}) and evaporative resistance (R_{et}) results (with mean and standard error) from sweating guarded hotplate testing

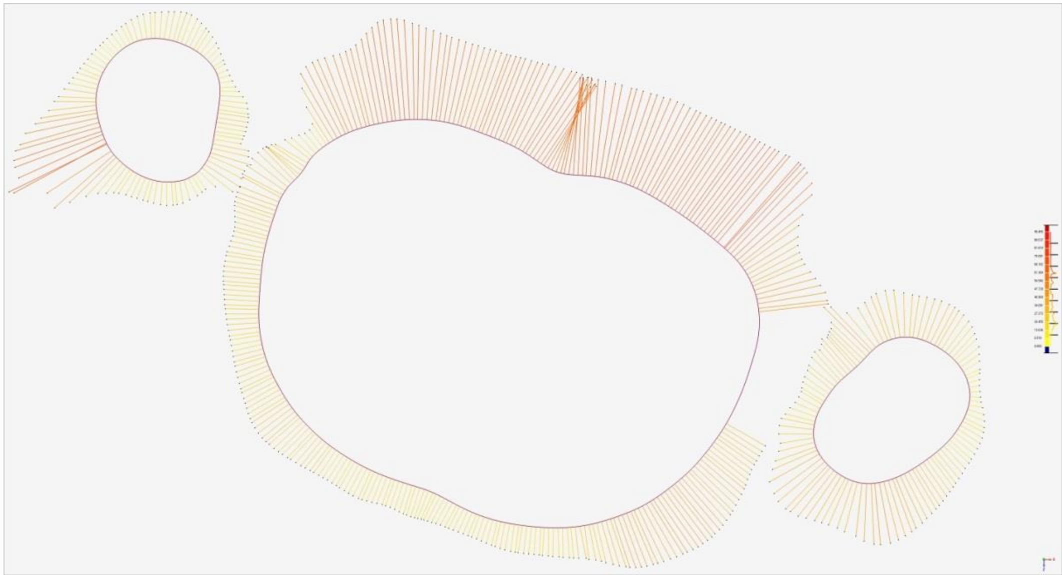
1) R_{ct}

Type	Sample			Mean	SEM
	1	2	3		
Proshield®	0.0821	0.0865	0.0783	0.0823	0.0024
Tyvek®	0.1031	0.0944	0.1144	0.1040	0.0058
Tychem®	0.1058	0.1099	0.1090	0.1082	0.0012
Gulf	0.1041	0.1157	0.1043	0.1080	0.0038
Cold	0.1588	0.1342	0.1589	0.1506	0.0082

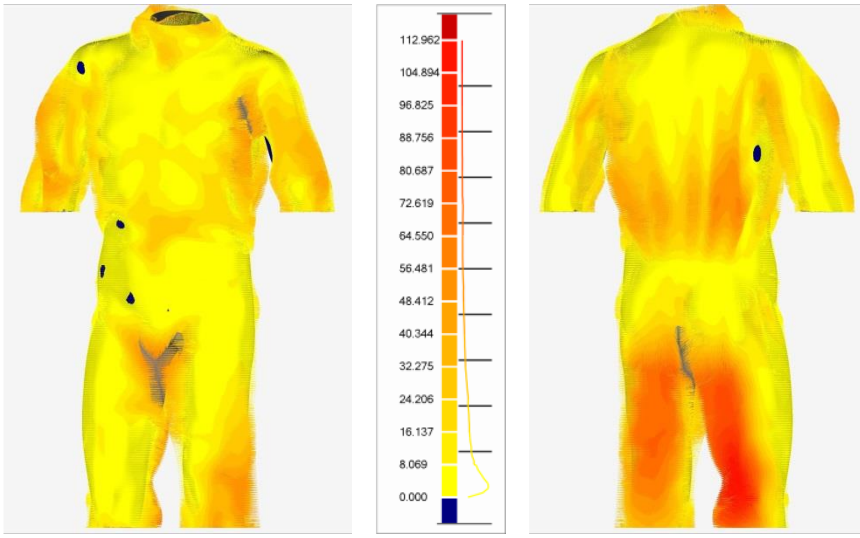
2) R_{et}

Type	Sample			Mean	SEM
	1	2	3		
Proshield®	7.276	9.32	8.29	8.30	0.59
Tyvek®	11.14	15.67	15.31	14.04	1.45
Tychem®	52.99	44.25	43.45	46.90	3.06
Gulf	10.48	10.41	11.53	10.81	0.36
Cold	14.87	17.40	17.83	16.70	0.92

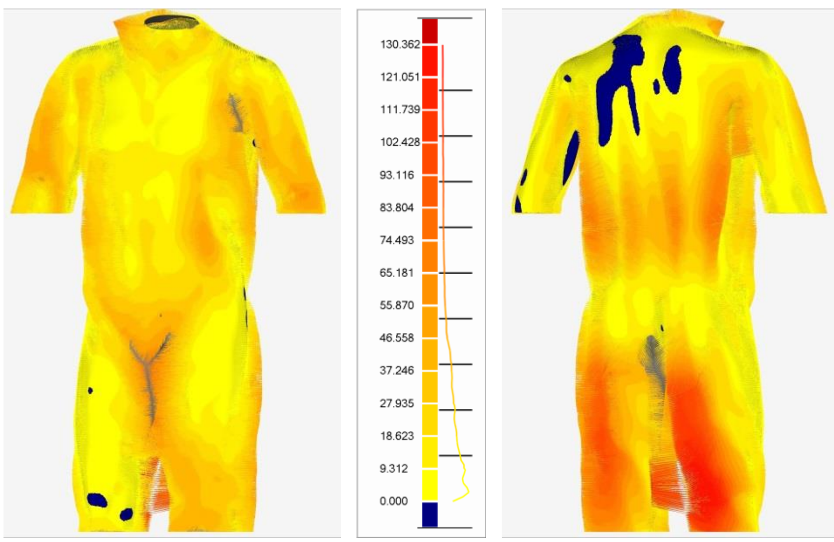
Appendix 3. Cross-sectional view of 3-D deviation spectrum



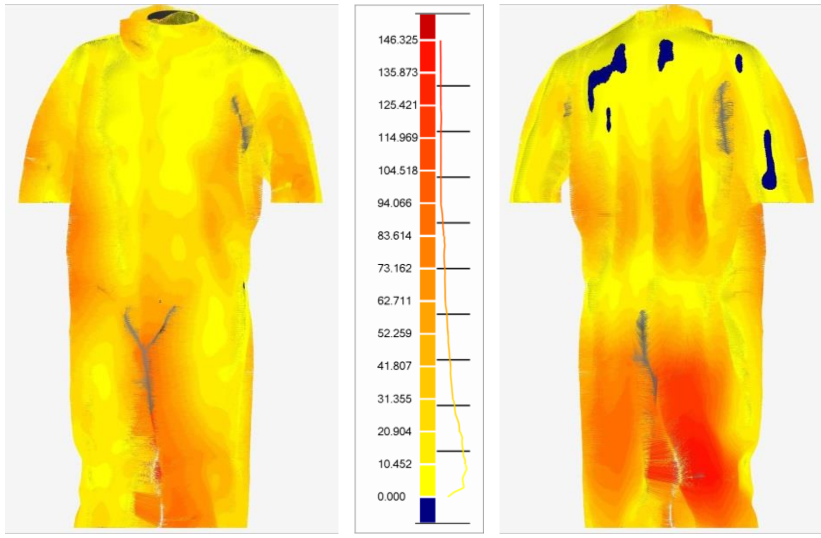
Appendix 4. Air gap distributions of the twelve 3-D scanned coveralls



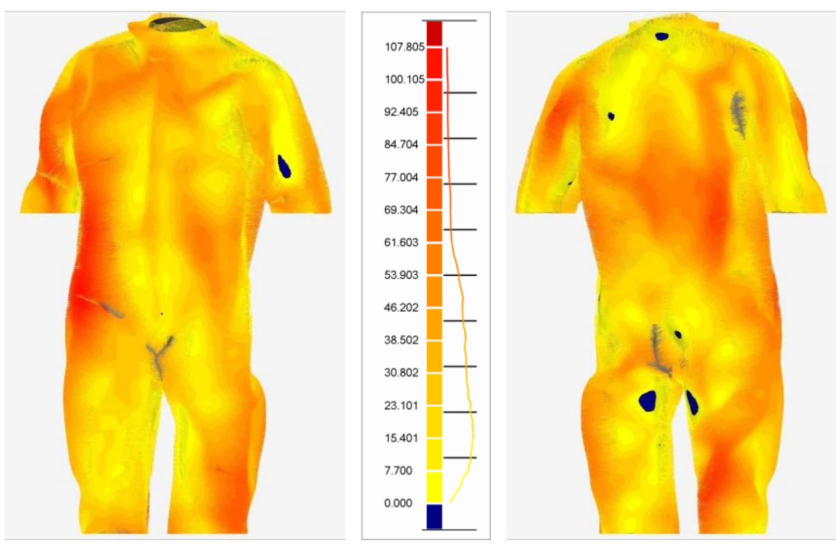
1) front and back views of Tyvek® - Medium



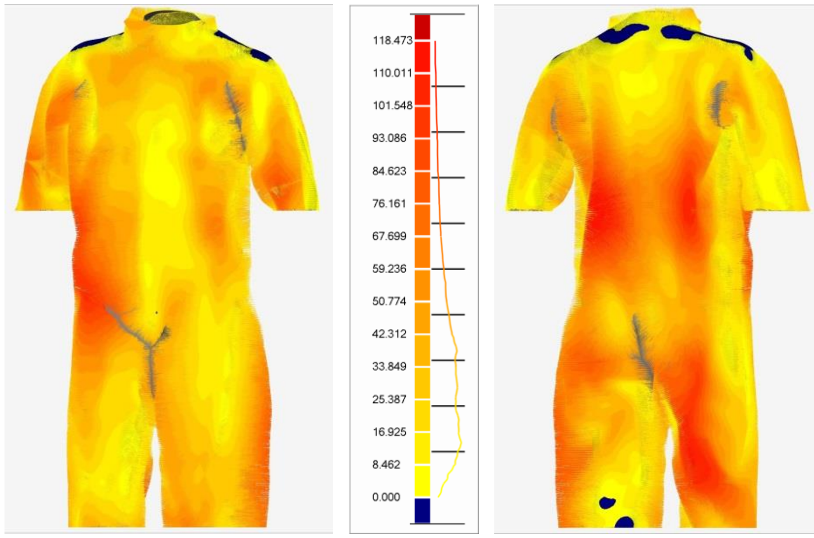
2) front and back views of Tyvek® - Large



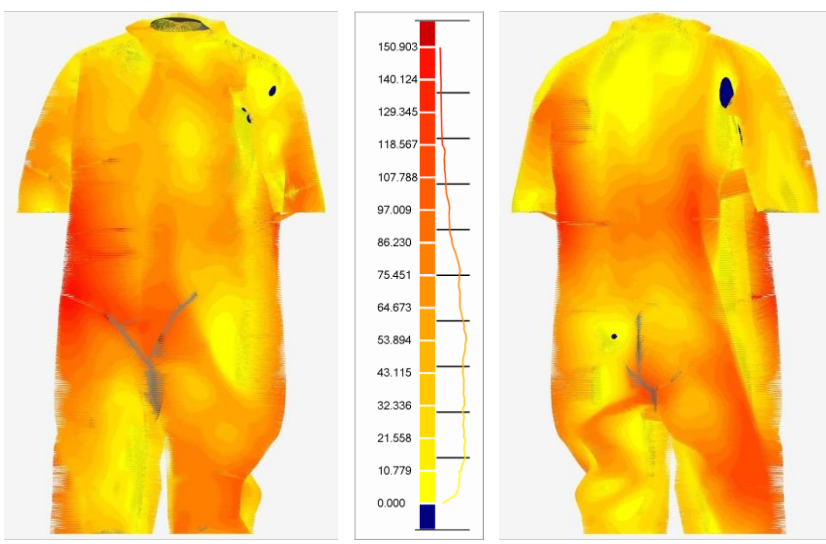
3) front and back views of Tyvek® - 2X-Large



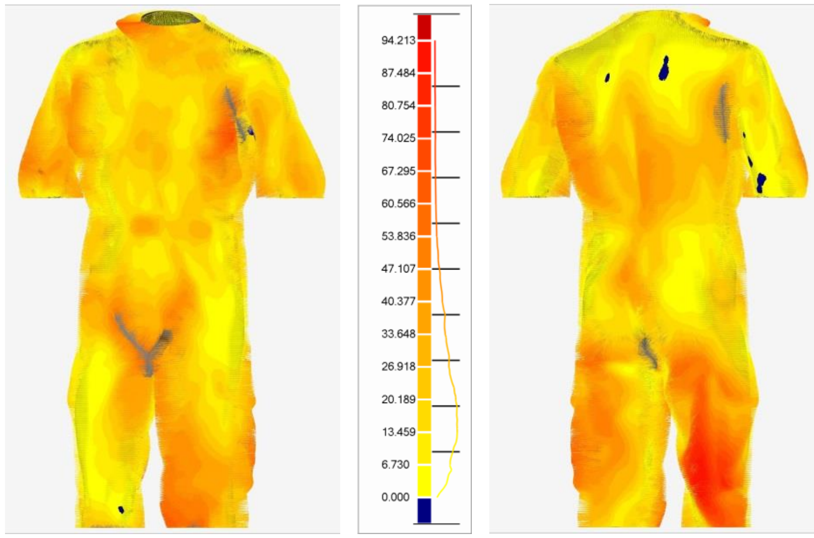
4) front and back views of Tychem® - Medium



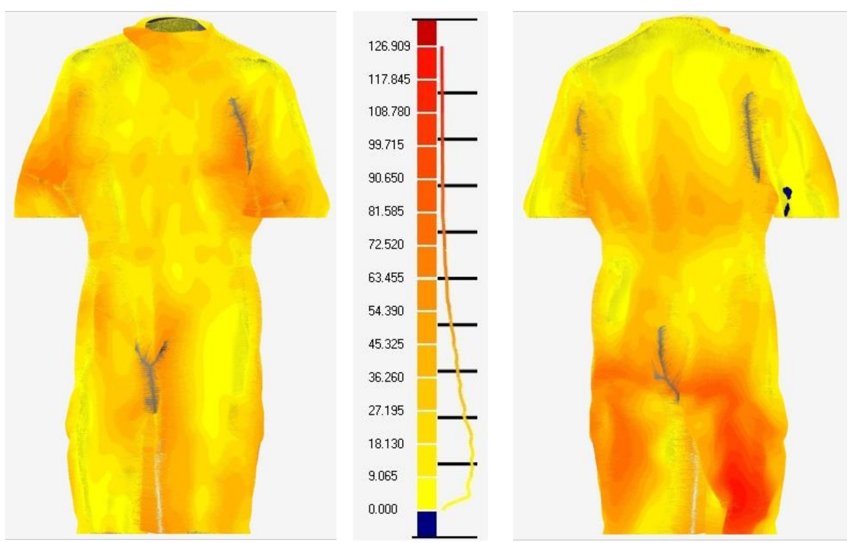
5) front and back views of Tychem® - Large



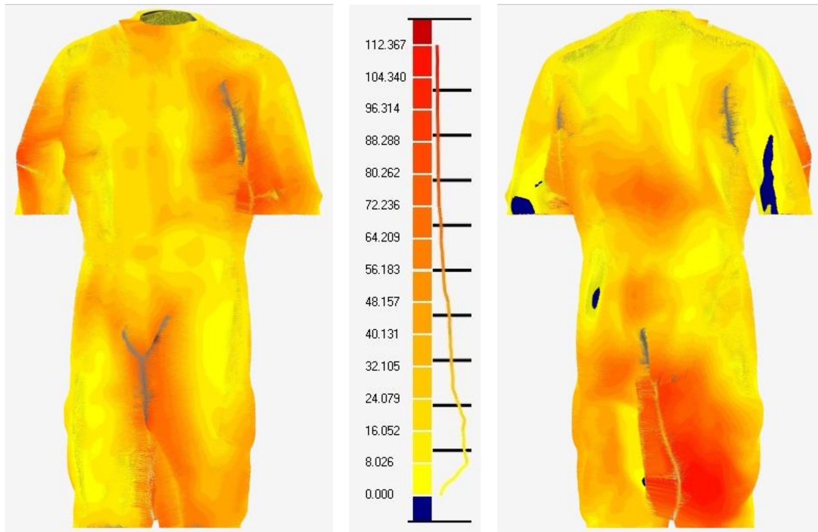
6) front and back views of Tychem® - 2X-Large



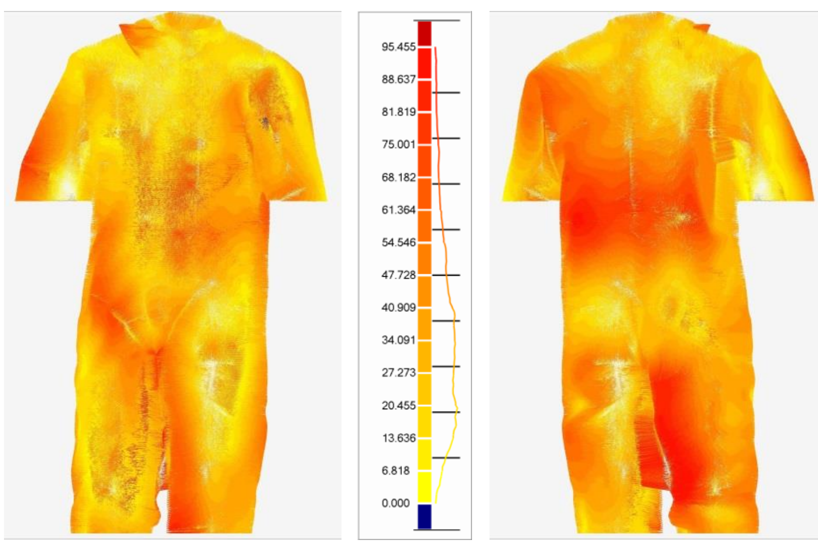
7) front and back views of Gulf – Medium



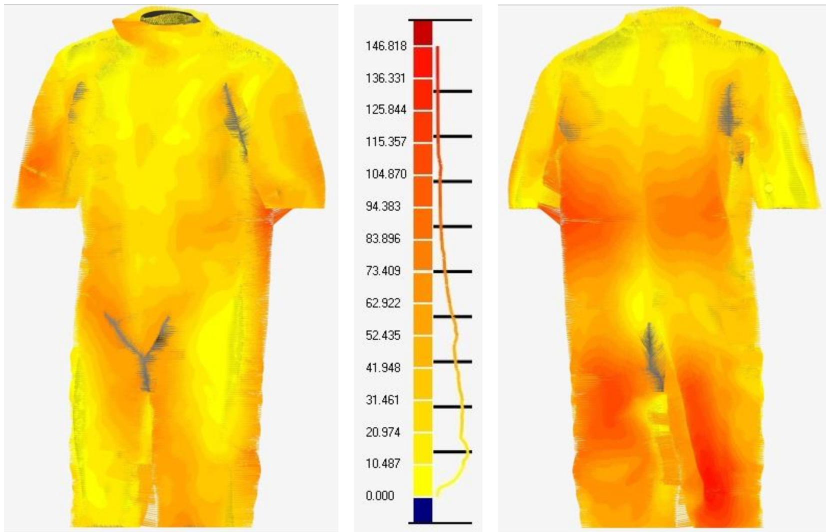
8) front and back views of Gulf – Large



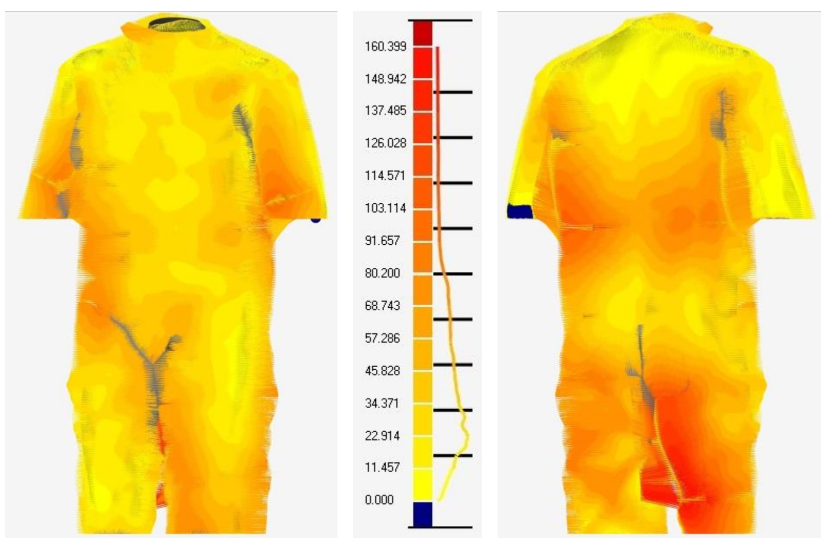
9) front and back views of Gulf – 2X-Large



10) front and back views of Cold – Medium

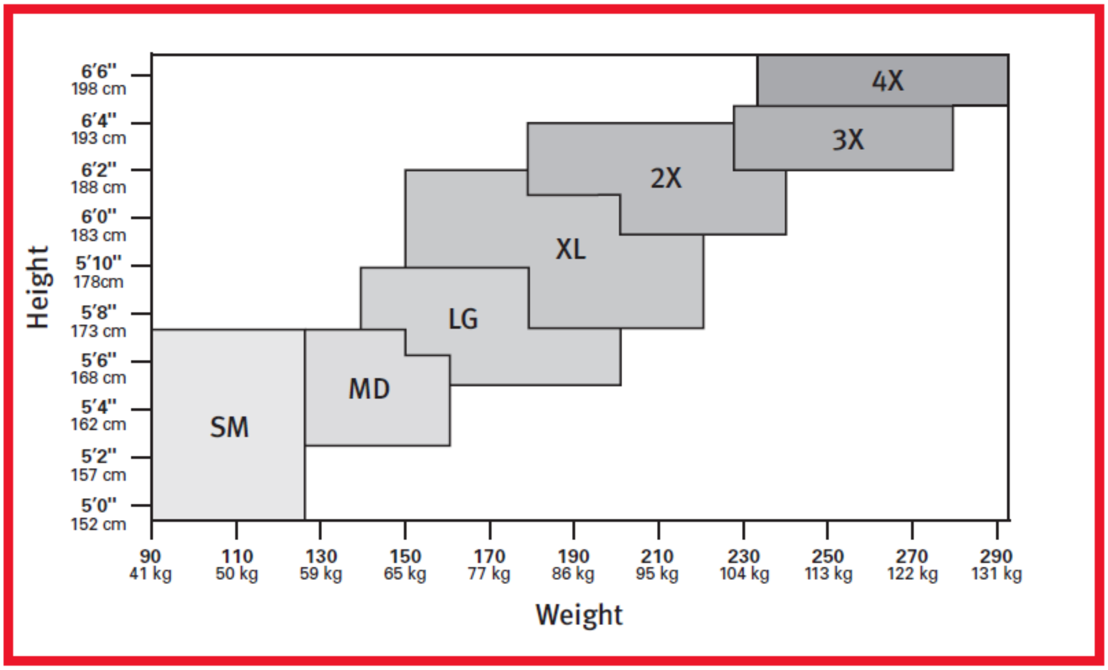


11) front and back views of Cold – Large



12) front and back views of Cold – 2X-Large

Appendix 5. Non-encapsulated suit and coverall sizing chart



(adopted from online Dupont Personal Protection Product Catalog, retrieved January 27, 2014, http://safespec.dupont.com/safespec/media/documents/dpp_catalog.pdf)

Appendix 6. Air gap size and volume of microclimate for twelve coveralls

Type	Size	Air gap (mm)				Vm (mm^3)
		AAGS	Standard deviation	Maximal air gap size	Minimal air gap size	
Tyvek	Medium	18.55	18.70	112.96	0.00	2.32×10^7
	Large	25.31	22.41	130.36	0.00	3.08×10^7
	2X-Large	33.05	27.13	146.33	0.00	4.32×10^7
Tychem	Medium	31.47	19.21	107.81	0.00	4.02×10^7
	Large	35.43	22.60	118.47	0.00	4.67×10^7
	2X-Large	50.44	29.93	150.90	0.00	6.59×10^7
Gulf	Medium	23.38	14.73	94.21	0.00	2.95×10^7
	Large	29.02	20.45	126.91	0.00	3.71×10^7
	2X-Large	29.58	21.01	112.37	0.00	3.84×10^7
Cold	Medium	34.68	18.49	95.46	0.00	4.67×10^7
	Large	40.25	25.43	146.82	0.00	5.21×10^7
	2X-Large	42.84	25.92	160.40	0.00	5.77×10^7

Appendix 7. Clothing thermal insulation (R_{ct-c}) and evaporative resistance (R_{et-c}) values from sweating manikin testing

Type	size	R_{ct-c} ($m^2 \cdot °C/W$)	R_{et-c} ($m^2 \cdot kPa/W$)
Tyvek®	Medium	0.189	36.5
	Large	0.186	42.6
	2X-large	0.192	40.5
Tychem®	Medium	0.192	346.0
	Large	0.190	319.8
	2X-large	0.187	338.3
Gulf	Medium	0.242	32.8
	Large	0.257	35.9
	2X-large	0.259	34.2
Cold	Medium	0.258	52.3
	Large	0.266	55.6
	2X-large	0.262	50.6

Appendix 8. Subjective rating scales used in the study

Rating of Perceived Exertion

6 –

7 – very, very light

8 –

9 – very light

10 –

11 – fairly light

12 –

13 – somewhat hard

14 –

15 – hard

16 –

17 – very hard

18 –

19 – very, very hard

20 –

Subjective Rating Scales on Hotness in Clothing

0 – no change

1 – slightly hot

2 – hot

3 – very hot

4 – extremely hot

Subjective Rating Scales on Wetness in Clothing

0 – no change

1 – slightly wet

2 – wet

3 – very wet

4 – extremely wet

Subjective Rating Scales on Restriction to Movements

0 – no restriction

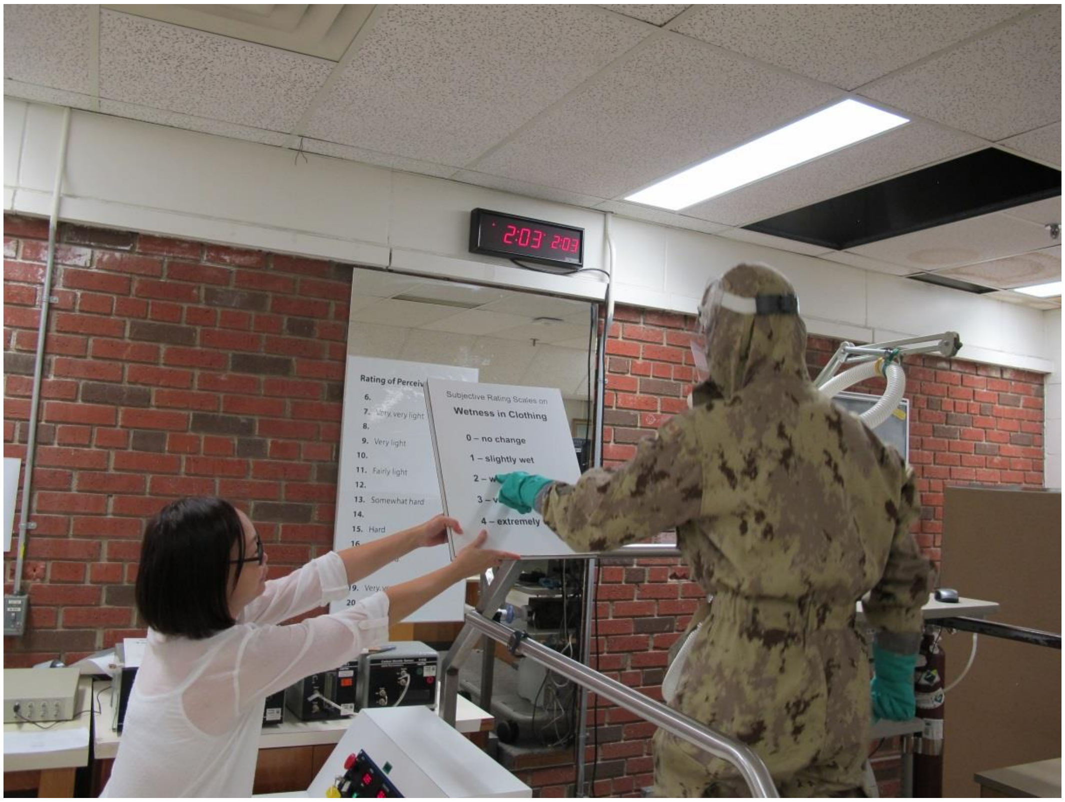
1 – slightly restricted

2 – restricted

3 – very restricted

4 – extremely restricted

Appendix 9. Subjective rating data collection



Appendix 10. Summary of Pearson correlations in relation to physiological responses and fabric/garment properties (two-tailed)

Comparison			r value	p value	N
ΔT_c	vs.	R_{ct}	0.549	< 0.01	60
ΔT_c	vs.	R_{et}	**0.795**	< 0.01	60
ΔT_c	vs.	THL	-0.514	< 0.01	60
ΔT_c	vs.	R_{ct-c}	0.414	< 0.01	60
ΔT_c	vs.	R_{et-c}	0.789	< 0.01	60
ΔT_c	vs.	Thickness at 5gf	**0.704**	< 0.01	60
ΔT_{sk}	vs.	R_{ct}	0.348	< 0.01	60
ΔT_{sk}	vs.	R_{et}	**0.519**	< 0.01	60
ΔT_{sk}	vs.	THL	-0.330	< 0.05	60
ΔT_{sk}	vs.	R_{ct-c}	0.239	NS	60
ΔT_{sk}	vs.	R_{et-c}	0.511	< 0.01	60
ΔT_{sk}	vs.	Thickness at 5gf	**0.411**	< 0.01	60
Average HIC	vs.	R_{ct}	0.693	<0.01	60
Average HIC	vs.	R_{et}	**0.745**	<0.01	60
Average HIC	vs.	THL	-0.667	<0.01	60
Average HIC	vs.	R_{ct-c}	0.569	<0.01	60
Average HIC	vs.	R_{et-c}	0.712	<0.01	60
Average HIC	vs.	Thickness at 5gf	**0.740**	< 0.01	60
Average WIC	vs.	R_{ct}	**0.696**	<0.01	60
Average WIC	vs.	R_{et}	**0.591**	<0.01	60
Average WIC	vs.	THL	-0.682	<0.01	60
Average WIC	vs.	R_{ct-c}	0.591	<0.01	60
Average WIC	vs.	R_{et-c}	0.541	<0.01	60
Average WIC	vs.	Thickness at 5gf	0.635	< 0.01	60
Average VO_{2-N}	vs.	Garment weight	**0.456**	< 0.01	45
Average VO_{2-N}	vs.	Tensile LT	-0.023	NS	
Average VO_{2-N}	vs.	Tensile WT	-0.493	<0.01	45
Average VO_{2-N}	vs.	Tensile RT	0.500	<0.01	45
Average VO_{2-N}	vs.	Bending B	0.373	<0.05	45
Average VO_{2-N}	vs.	Bending 2HB	**0.413**	<0.01	45
Average VO_{2-N}	vs.	Shearing G	0.325	<0.05	45
Average VO_{2-N}	vs.	Shearing 2HG	0.340	<0.05	45
Average VO_{2-N}	vs.	Shearing 2HG5	0.295	<0.05	45

Average $VO_{2\text{-}N}$	vs.	Compression LC	-0.237	NS	45
Average $VO_{2\text{-}N}$	vs.	Compression WC	0.477	<0.01	45
Average $VO_{2\text{-}N}$	vs.	Compression RC	0.422	<0.01	45
Average $VO_{2\text{-}N}$	vs.	Surface MIU	-0.449	<0.01	45
Average $VO_{2\text{-}N}$	vs.	Surface MMD	-0.242	NS	45
Average $VO_{2\text{-}N}$	vs.	Surface SMD	-0.064	NS	45
Average $VO_{2\text{-}N}$	vs.	Thickness at 5gf	0.534	<0.01	45
Average RPE	vs.	Rct	0.567	<0.01	60
Average RPE	vs.	Ret	**0.619**	<0.01	60
Average RPE	vs.	THL	-0.540	<0.01	60
Average RPE	vs.	$R_{ct\text{-}c}$	0.474	<0.01	60
Average RPE	vs.	$R_{et\text{-}c}$	0.598	<0.01	60
Average RPE	vs.	Garment weight	0.480	<0.01	59
Average RPE	vs.	Tensile LT	0.173	NS	45
Average RPE	vs.	Tensile WT	-0.517	<0.01	45
Average RPE	vs.	Tensile RT	0.549	<0.01	45
Average RPE	vs.	Bending B	0.549	<0.01	45
Average RPE	vs.	Bending 2HB	0.573	<0.01	45
Average RPE	vs.	Shearing G	0.514	<0.01	45
Average RPE	vs.	Shearing 2HG	0.525	<0.01	45
Average RPE	vs.	Shearing 2HG5	0.490	<0.01	45
Average RPE	vs.	Compression LC	-0.440	<0.01	45
Average RPE	vs.	Compression WC	0.471	<0.01	45
Average RPE	vs.	Compression RC	0.578	<0.01	45
Average RPE	vs.	Surface MIU	-0.414	<0.01	45
Average RPE	vs.	Surface MMD	-0.444	<0.01	45
Average RPE	vs.	Surface SMD	-0.269	NS	45
Average RPE	vs.	Thickness at 5 gf	**0.653**	<0.01	60
Δ HR	vs.	R_{ct}	0.618	<0.01	60
Δ HR	vs.	R_{et}	**0.720**	<0.01	60
Δ HR	vs.	THL	-0.590	<0.01	60
Δ HR	vs.	$R_{ct\text{-}c}$	0.501	<0.01	60
Δ HR	vs.	$R_{et\text{-}c}$	0.696	<0.01	60
Δ HR	vs.	Garment weight	0.436	<0.01	59
Δ HR	vs.	Tensile LT	0.287	NS	45
Δ HR	vs.	Tensile WT	-0.565	<0.01	45
Δ HR	vs.	Tensile RT	0.612	<0.01	45
Δ HR	vs.	Bending B	0.678	<0.01	45
Δ HR	vs.	Bending 2HB	0.696	<0.01	45
Δ HR	vs.	Shearing G	0.647	<0.01	45
Δ HR	vs.	Shearing 2HG	0.657	<0.01	45
Δ HR	vs.	Shearing 2HG5	0.625	<0.01	45

Δ HR	vs.	Compression LC	-0.575	<0.01	45
Δ HR	vs.	Compression WC	0.501	<0.01	45
Δ HR	vs.	Compression RC	0.697	<0.01	45
Δ HR	vs.	Surface MIU	-0.424	<0.01	45
Δ HR	vs.	Surface MMD	-0.580	<0.01	45
Δ HR	vs.	Surface SMD	-0.394	<0.01	45
Δ HR	vs.	Thickness at 5gf	**0.698**	<0.01	60
ΔPSI	vs.	R_{ct}	0.598	<0.01	60
ΔPSI	vs.	R_{et}	**0.774**	<0.01	60
ΔPSI	vs.	THL	-0.566	<0.01	60
ΔPSI	vs.	R_{ct-c}	0.467	<0.01	60
ΔPSI	vs.	R_{et-c}	0.758	<0.01	60
ΔPSI	vs.	Garment weight	0.431	<0.01	59
ΔPSI	vs.	Tensile LT	0.331	<0.05	45
ΔPSI	vs.	Tensile WT	-0.606	<0.01	45
ΔPSI	vs.	Tensile RT	0.659	<0.01	45
ΔPSI	vs.	Bending B	0.746	<0.01	45
ΔPSI	vs.	Bending 2HB	**0.763**	<0.01	45
ΔPSI	vs.	Shearing G	0.714	<0.01	45
ΔPSI	vs.	Shearing 2HG	0.725	<0.01	45
ΔPSI	vs.	Shearing 2HG5	0.692	<0.01	45
ΔPSI	vs.	Compression LC	-0.639	<0.01	45
ΔPSI	vs.	Compression WC	0.534	<0.01	45
ΔPSI	vs.	Compression RC	0.763	<0.01	45
ΔPSI	vs.	Surface MIU	-0.447	<0.01	45
ΔPSI	vs.	Surface MMD	-0.644	<0.01	45
ΔPSI	vs.	Surface SMD	-0.447	<0.01	45
ΔPSI	vs.	Thickness at 5gf	0.714	<0.01	60

Appendix 11. Output of standard multiple regression analysis

Regression

Descriptive Statistics

	Mean	Std. Deviation	N
delta_Tc	.9997	.59531	60
Thickness_at_5g	1.0850	.88204	60
Ret	19.1144	16.70133	60

Correlations

		delta_Tc	Thickness_at_5g	Ret
Pearson Correlation	delta_Tc	1.000	.704	.800
	Thickness_at_5g	.704	1.000	.605
	Ret	.800	.605	1.000
Sig. (1-tailed)	delta_Tc	.	.000	.000
	Thickness_at_5g	.000	.	.000
	Ret	.000	.000	.
N	delta_Tc	60	60	60
	Thickness_at_5g	60	60	60
	Ret	60	60	60

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	Ret, Thickness_at_5g[b]	.	Enter

a. Dependent Variable: delta_Tc

b. All requested variables entered.

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.846[a]	.716	.706	.32274	.716	71.872	2	57	.000

a. Predictors: (Constant), Ret, Thickness_at_5g
b. Dependent Variable: delta_Tc

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	14.972	2	7.486	71.872	.000[b]
	Residual	5.937	57	.104		
	Total	20.910	59			

a. Dependent Variable: delta_Tc
b. Predictors: (Constant), Ret, Thickness_at_5g

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Correlations			Collinearity Statistics	
		B	Std. Error	Beta			Zero-order	Partial	Part	Tolerance	VIF
1	(Constant)	.344	.070		4.934	.000					
	Thickness_at_5g	.234	.060	.346	3.908	.000	.704	.460	.276	.634	1.577
	Ret	.021	.003	.590	6.661	.000	.800	.662	.470	.634	1.577

a. Dependent Variable: delta_Tc

Collinearity Diagnostics[a]

Model	Dimension	Eigenvalue	Condition Index	Variance Proportions		
				(Constant)	Thickness_at_5g	Ret
1	1	2.581	1.000	.04	.03	.04
	2	.258	3.166	.93	.09	.26
	3	.161	4.003	.03	.88	.71

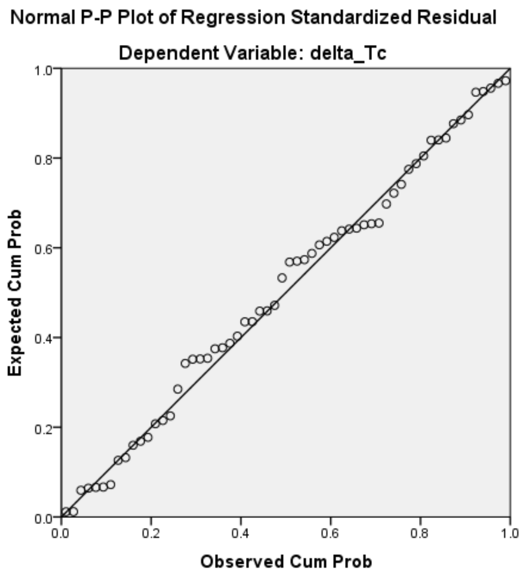
a. Dependent Variable: delta_Tc

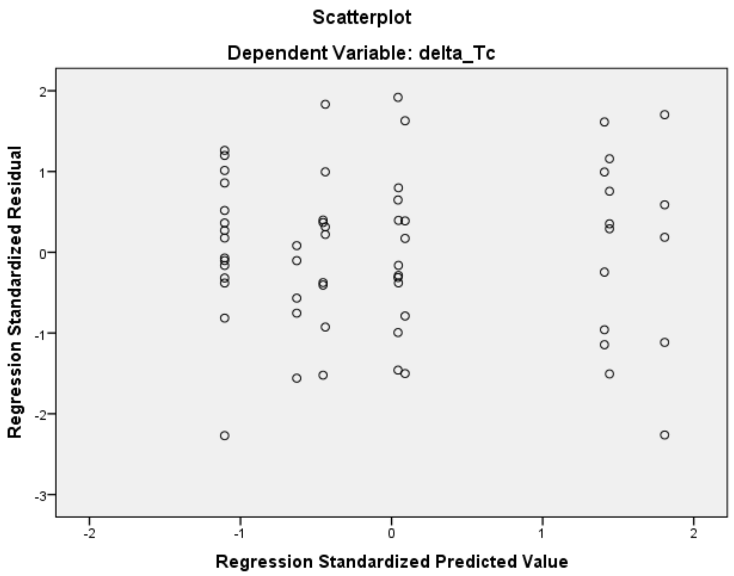
Residuals Statistics[a]

	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	.4429	1.9102	.9997	.50376	60
Std. Predicted Value	-1.105	1.807	.000	1.000	60
Standard Error of Predicted Value	.052	.096	.071	.014	60
Adjusted Predicted Value	.4248	1.9809	.9996	.50463	60
Residual	-.73294	.61896	.00000	.31722	60
Std. Residual	-2.271	1.918	.000	.983	60
Stud. Residual	-2.369	1.985	.000	1.011	60
Deleted Residual	-.80091	.66338	.00006	.33581	60
Stud. Deleted Residual	-2.474	2.040	-.002	1.027	60
Mahal. Distance	.521	4.228	1.967	1.098	60
Cook's Distance	.000	.181	.020	.032	60
Centered Leverage Value	.009	.072	.033	.019	60

a. Dependent Variable: delta_Tc

Charts


Normal P-P Plot of Regression Standardized Residual
Dependent Variable: delta_Tc
Expected Cum Prob
Observed Cum Prob
0.0
0.2
0.4
0.6
0.8
1.0


Scatterplot
Dependent Variable: delta_Tc
Regression Standardized Residual
Regression Standardized Predicted Value
-3
-2
-1
0
1
2